

# Effective theory approach to neutrinoless double beta decay

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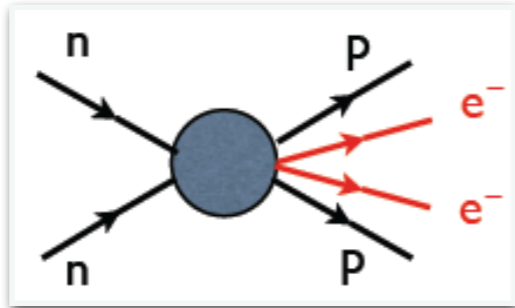


# Outline

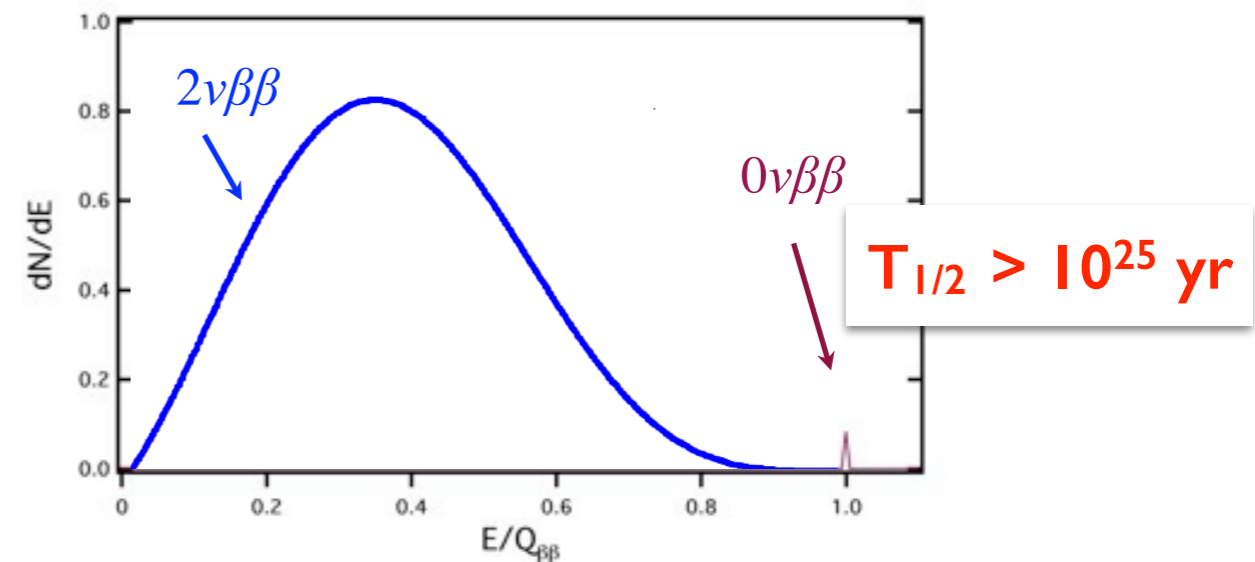
- Introduction:  $0\nu\beta\beta$  decay and Lepton Number Violation (LNV)
- Effective Field Theory (EFT) framework for LNV
- $0\nu\beta\beta$  from light Majorana  $\nu$  exchange
  - LO and N2LO chiral EFT potentials
  - *A new leading short-range contribution*
- $0\nu\beta\beta$  from (multi)TeV-scale dynamics
  - LO potentials & progress on hadronic matrix elements

# $0\nu\beta\beta$ and Lepton Number Violation

$$(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$$

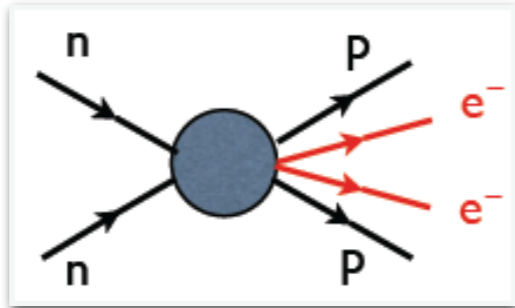


Lepton number changes by two units:  $\Delta L=2$

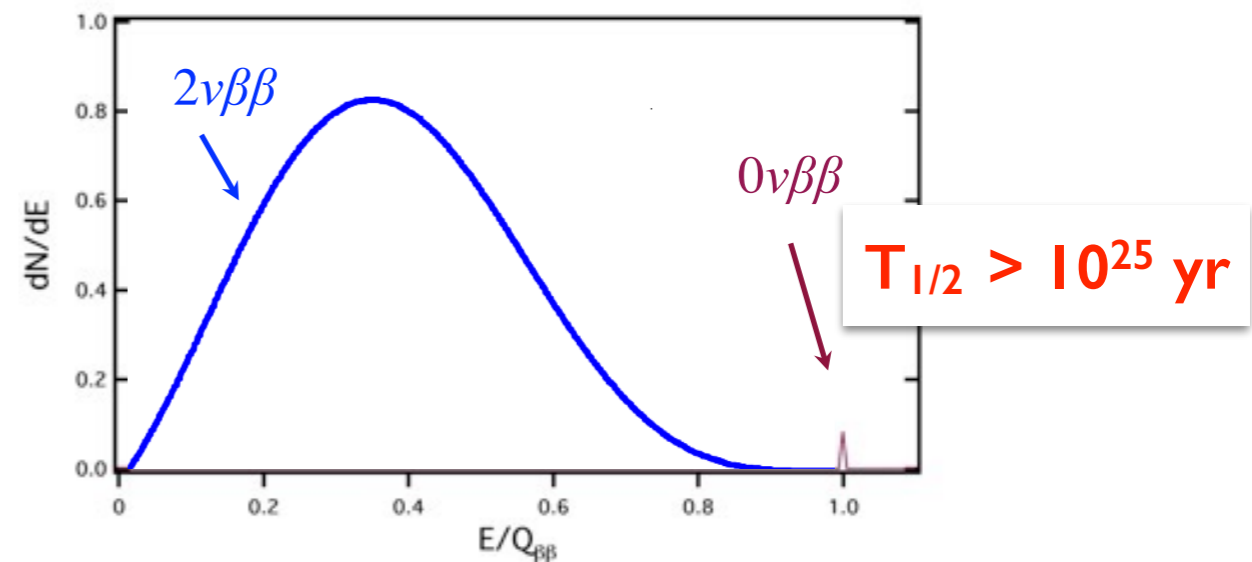


# $0\nu\beta\beta$ and Lepton Number Violation

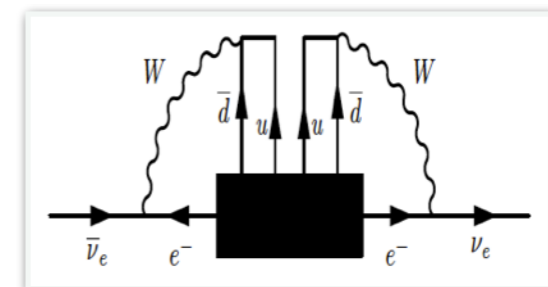
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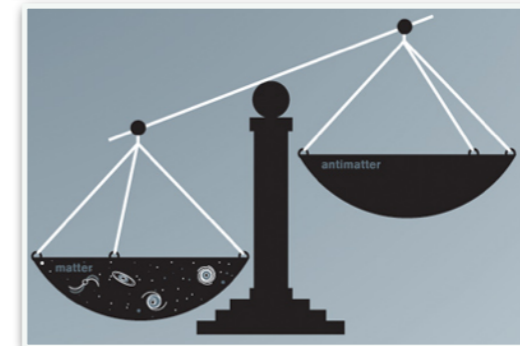
Lepton number changes by two units:  $\Delta L=2$



- B-L conserved in SM  $\rightarrow 0\nu\beta\beta$  observation would signal new physics
- Demonstrate that neutrinos are Majorana fermions
- Establish a key ingredient to generate the baryon asymmetry via leptogenesis



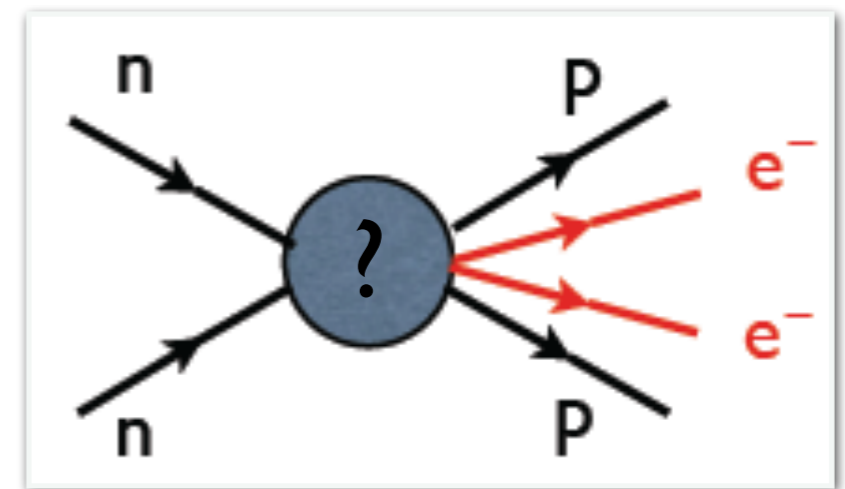
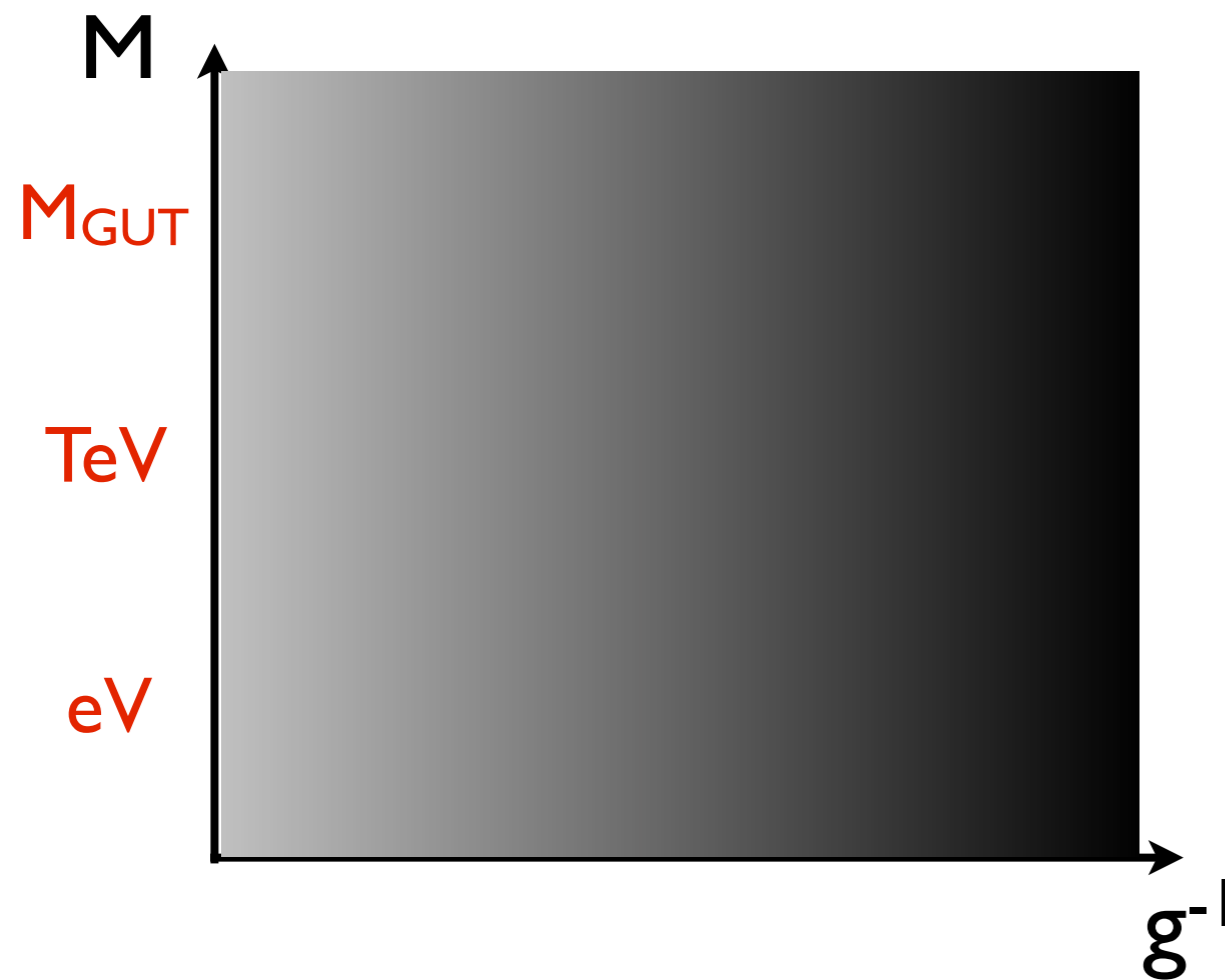
Shechter-  
Valle 1982



Fukujita-  
Yanagida  
1987

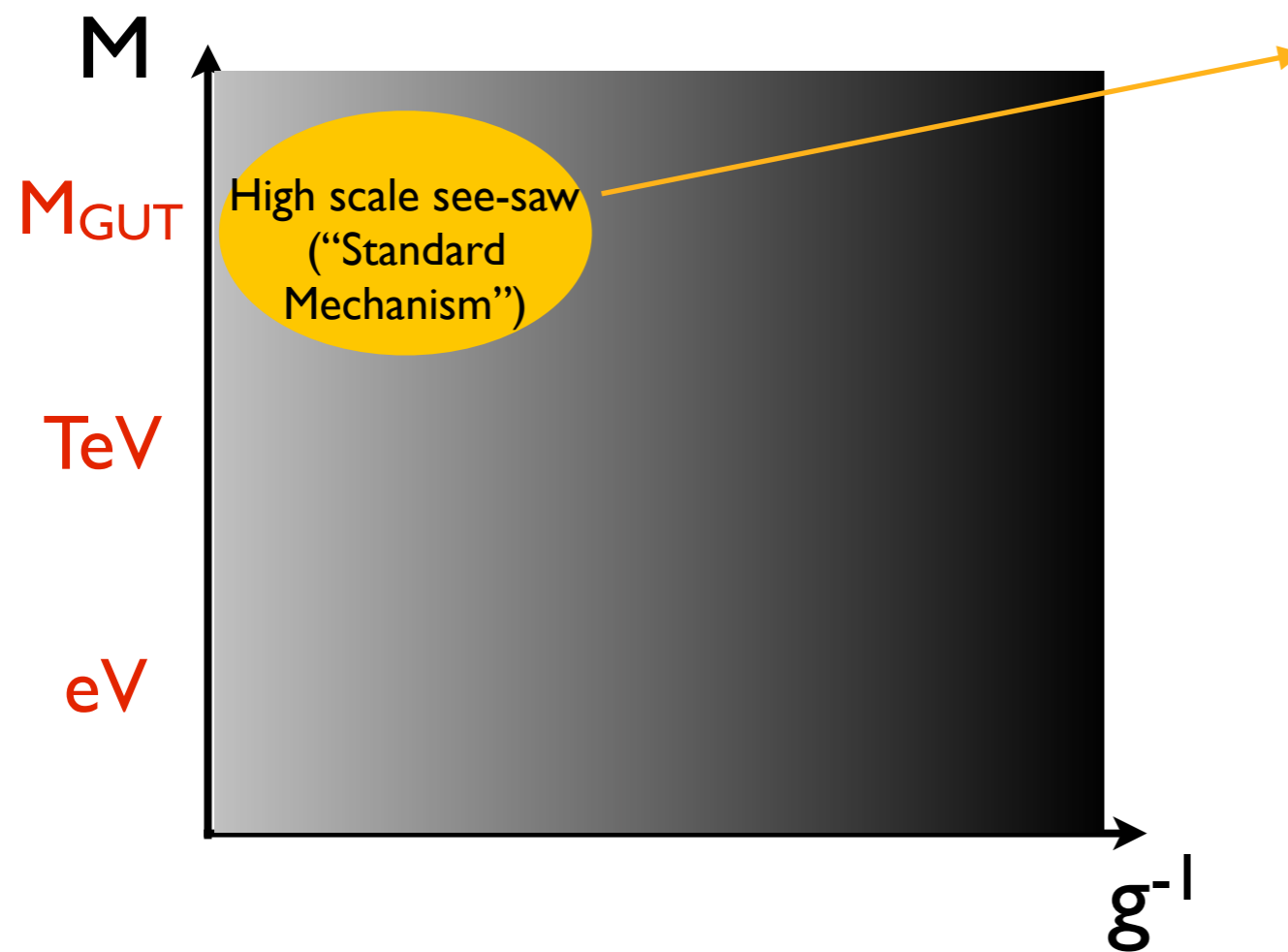
# $0\nu\beta\beta$ and Lepton Number Violation

- Ton-scale  $0\nu\beta\beta$  searches will probe LNV from a variety of mechanisms

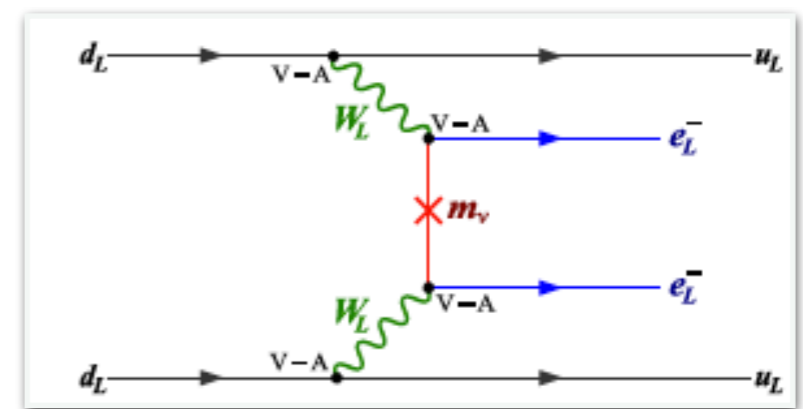


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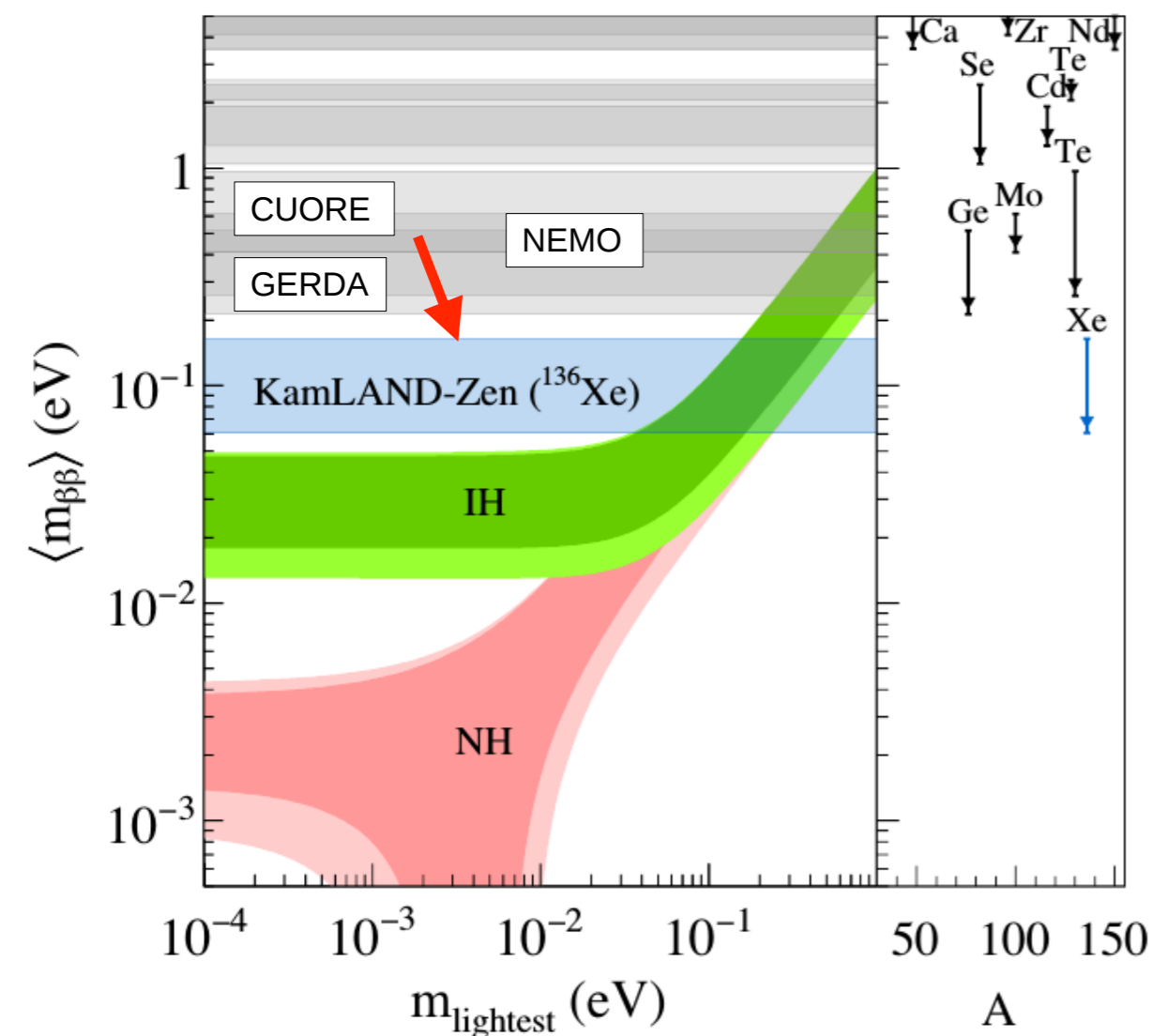
LNV dynamics at  $M \gg \text{TeV}$ :  
leaves as the only low-energy footprint  
light Majorana neutrino



$$A \propto m_{\beta\beta} \equiv \sum_i U_{ei}^2 m_i$$

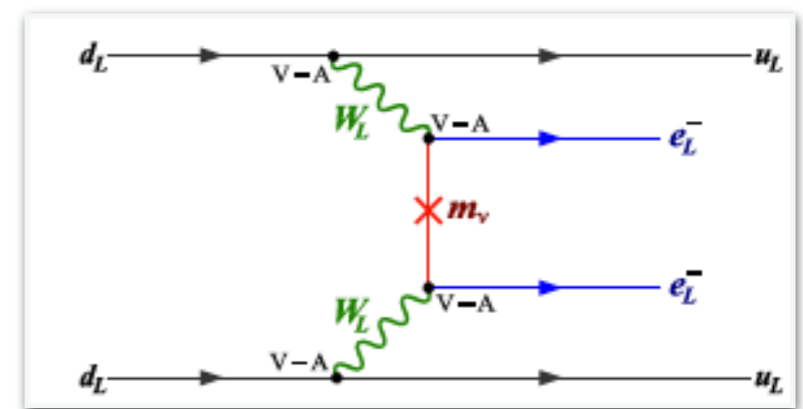
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KamLAND-Zen coll., '16

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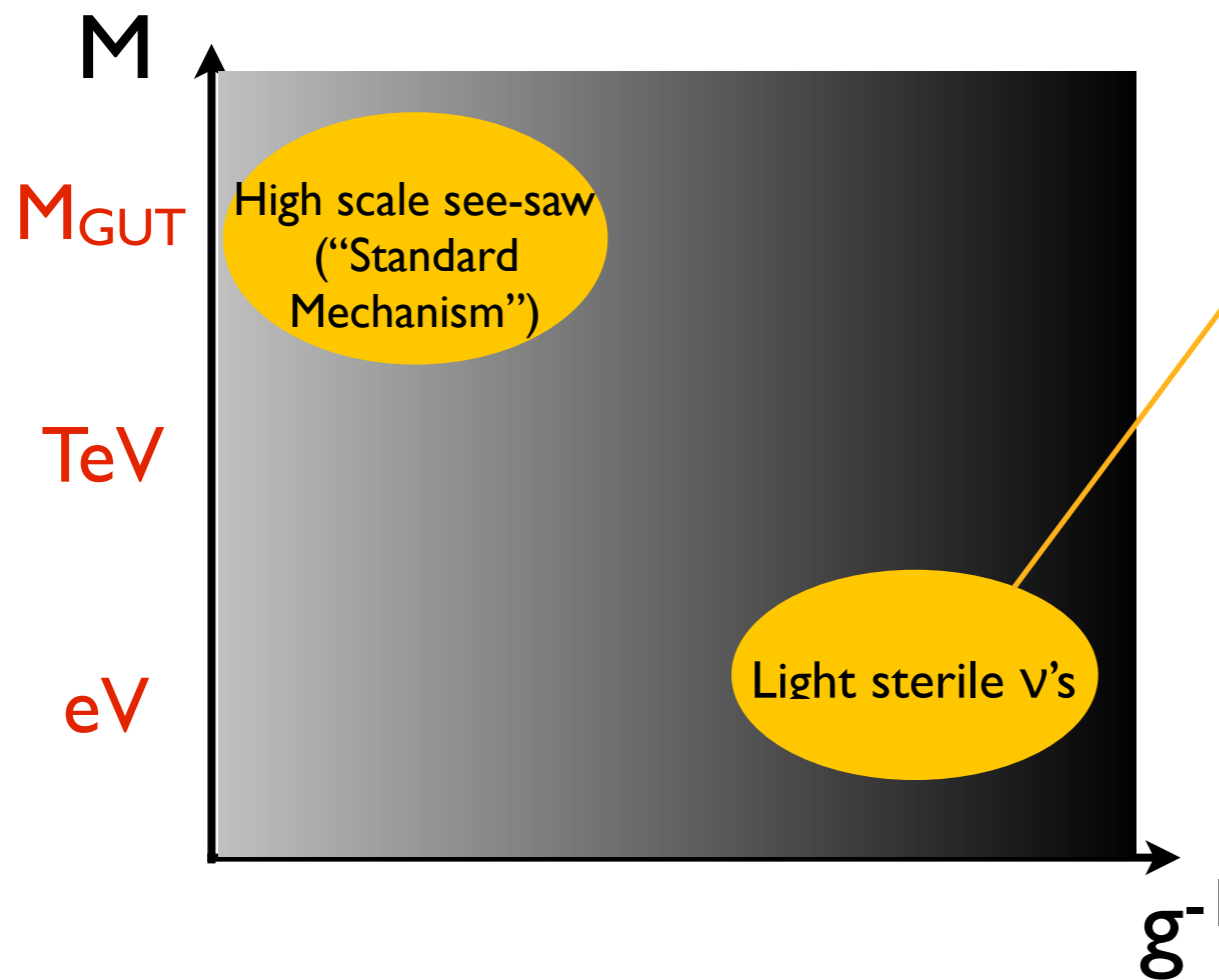
Clear interpretation framework and  
sensitivity goals (“inverted hierarchy”).

Requires difficult nuclear matrix elements:  
30-50% uncertainty (spread)

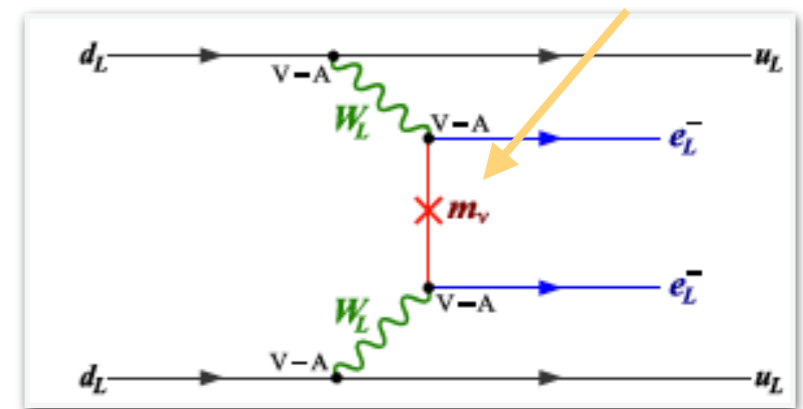
But only limited class of models!

# $0\nu\beta\beta$ and Lepton Number Violation

- Ton-scale  $0\nu\beta\beta$  searches will probe LNV from a variety of mechanisms

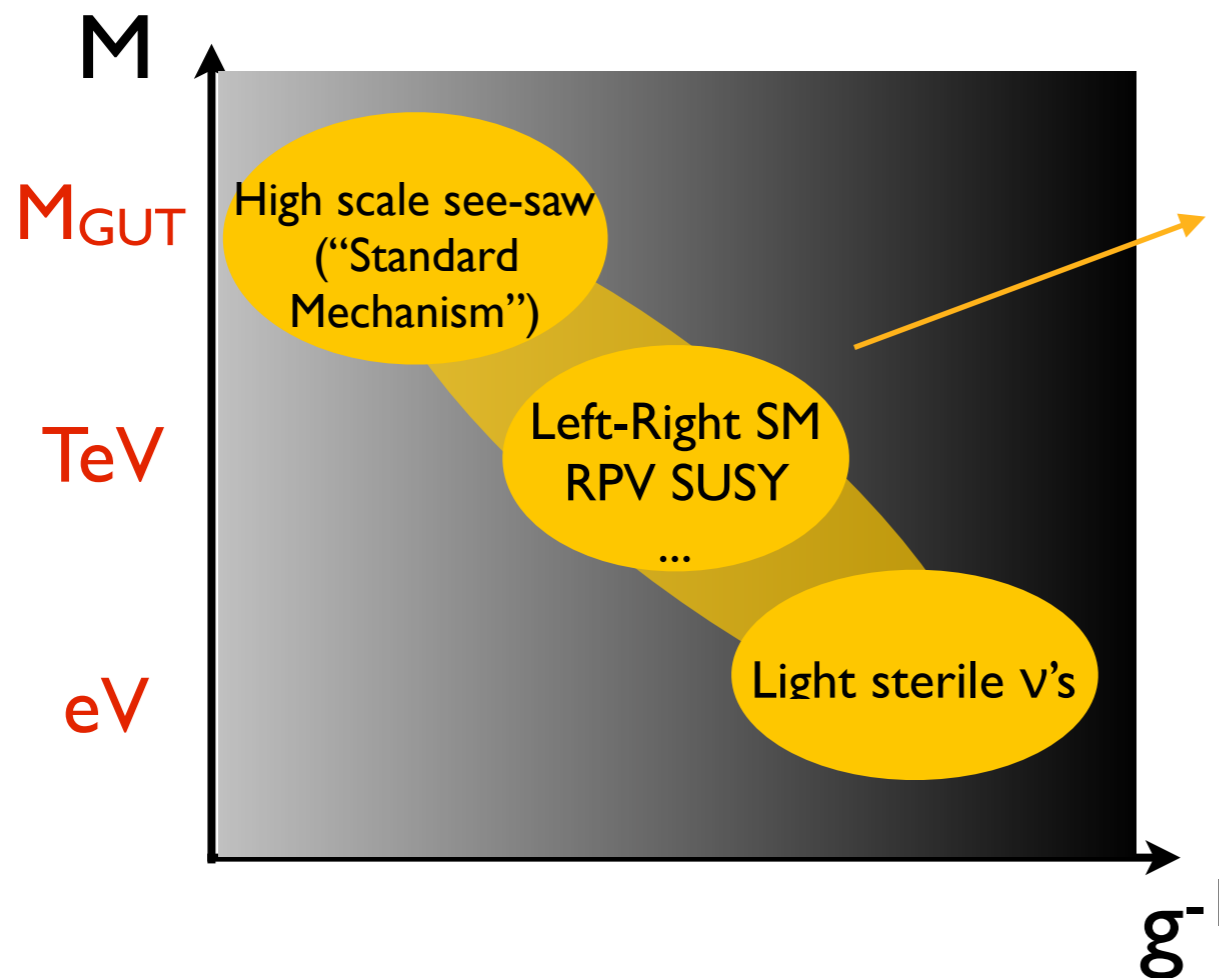


LNv dynamics at  $M_R \sim eV \rightarrow GeV$ :  
additional light Majorana states



# $0\nu\beta\beta$ and Lepton Number Violation

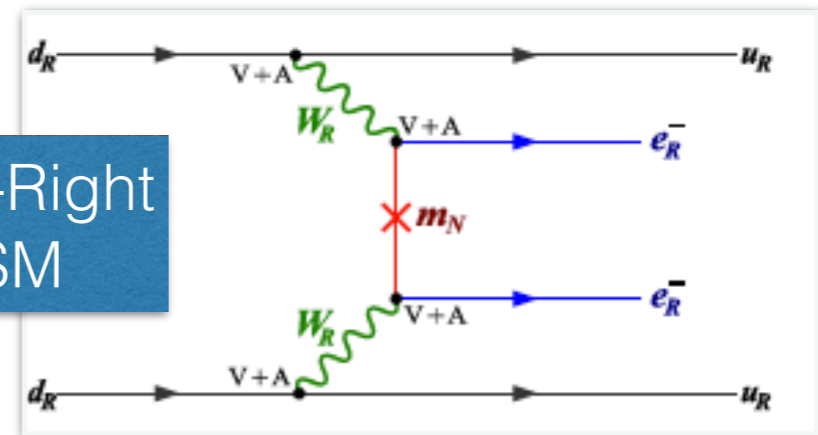
- Ton-scale  $0\nu\beta\beta$  searches will probe LNV from a variety of mechanisms



LNV dynamics could be at any scale  $> \text{eV}$ .  
For  $M \sim 1\text{-}100 \text{ TeV}$  one expects

- (i) New contributions to  $0\nu\beta\beta$  not directly related to light neutrino mass;
- (ii) Collider signatures, such as  $pp \rightarrow eejj$

Left-Right  
SM



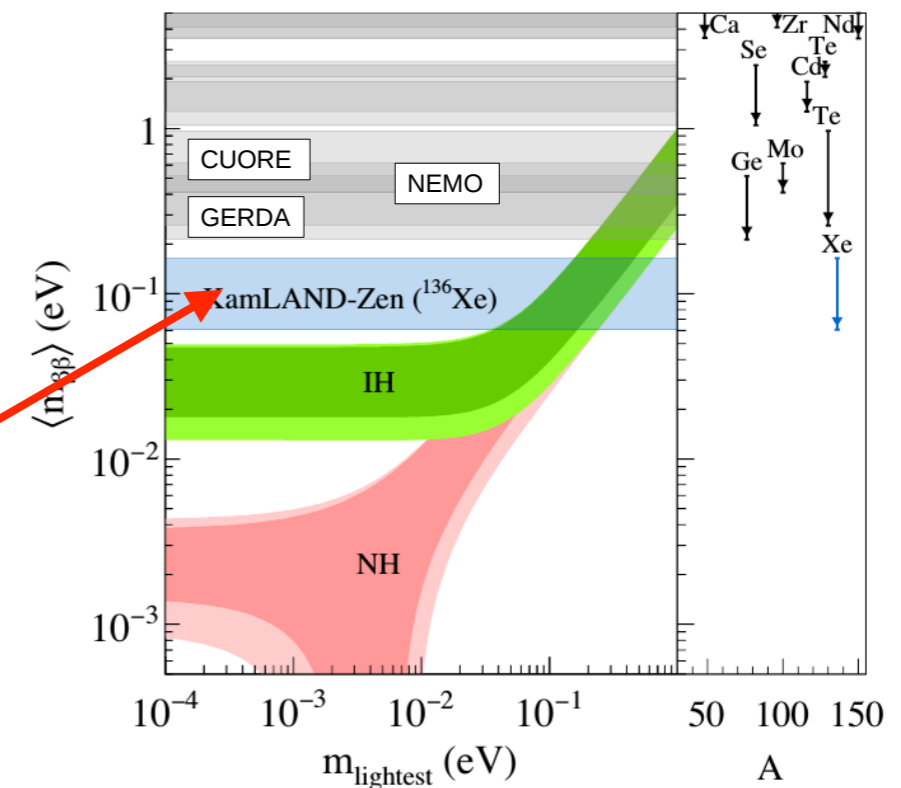
Discovery potential and interpretation of null results depend on a  
different set of (equally uncertain) hadronic and nuclear matrix elements

# Effective theory framework

- Impact of  $0\nu\beta\beta$  searches most efficiently analyzed in EFT framework:

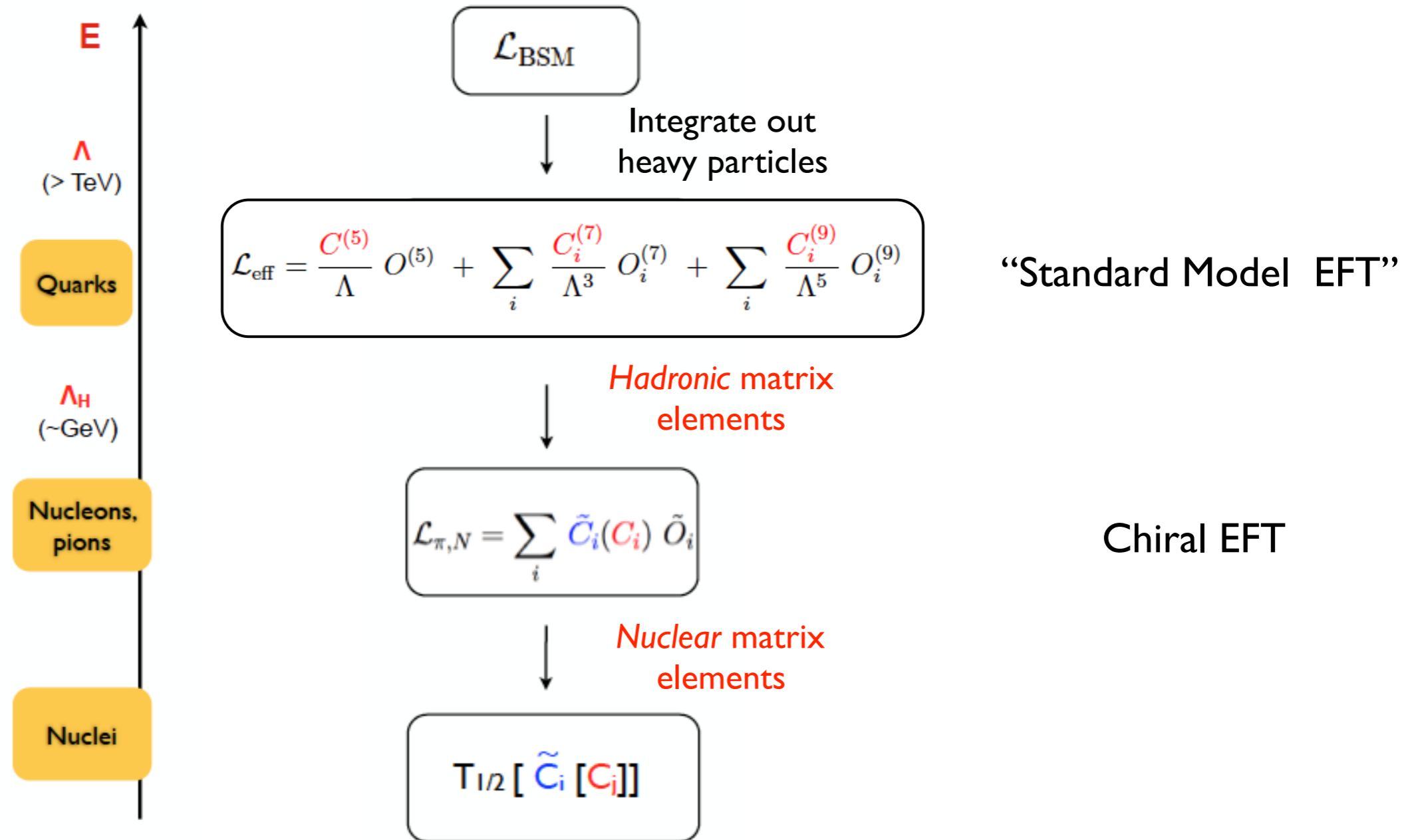
1. Systematically classify sources of Lepton Number Violation and relate  $0\nu\beta\beta$  to other LNV processes (such as  $pp \rightarrow eejj$  at the LHC)

2. Organize contributions to hadronic and nuclear matrix elements  
 $\Rightarrow$  “controllable” uncertainties

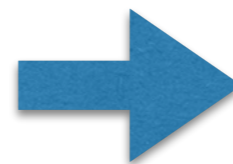


KamLAND-Zen coll., '16

# Effective theory framework



Chain of EFTs +  
hadronic & nuclear matrix elements



$$T_{1/2}[\tilde{C}_i[C_i]]$$

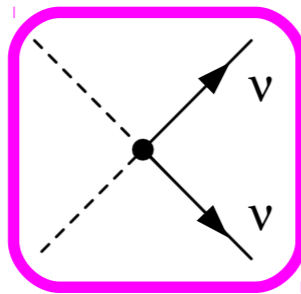
# High-scale effective Lagrangian

- $\Delta L=2$  operators appear at  $\text{dim} = 5, 7, 9, \dots$

$$\mathcal{L}_{\text{eff}}^{\Delta L=2} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)} + \dots$$

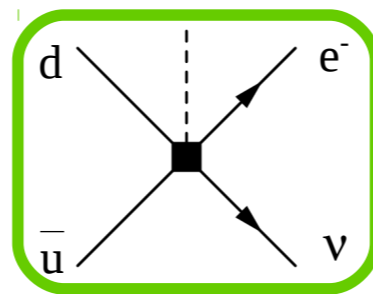
- One operator

Weinberg 1979



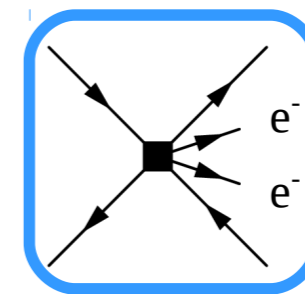
- Twelve operators

Lehman 1410.4193



- Eleven 6-fermion operators

Graesser 1606.04549

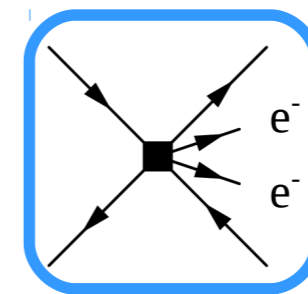
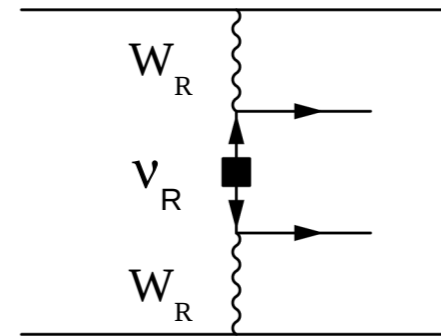
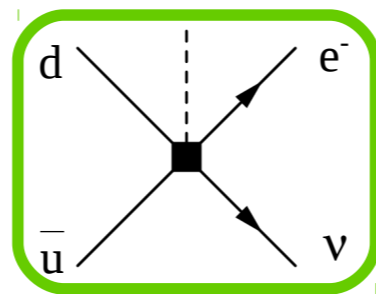
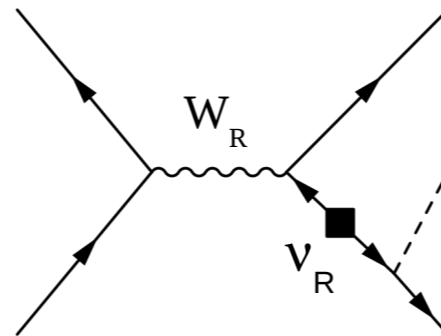
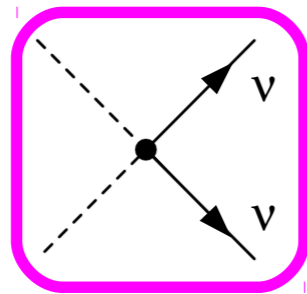
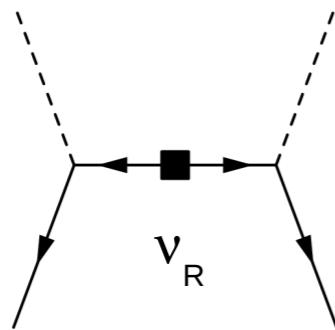


# High-scale effective Lagrangian

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Model  
realization:  
Left-Right SM



Systematic  
“unpacking”

Babu-Leung  
hep-ph/  
0106054

Bonnet et al  
1212.3045

Helo et al  
1602.03362

For  $\Lambda \sim \text{TeV}$ s,  
higher dim. ops.  
compete due  
to smallness of  
Yukawa  
couplings

# GeV-scale effective Lagrangian

- When the dust settles, get three classes of  $\Delta L=2$  operators

$$v = \left(\sqrt{2}G_F\right)^{-1/2} \quad \frac{v^2}{\Lambda} \quad (\text{dim-3})$$



$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2}m_{\beta\beta} \nu_{eL}^T C \nu_{eL} + C_\Gamma \bar{e} \Gamma C \bar{\nu}^T O_{2q}^\Gamma + C_{\Gamma'} \bar{e} \Gamma' e^c O_{4q}^{\Gamma'}$$

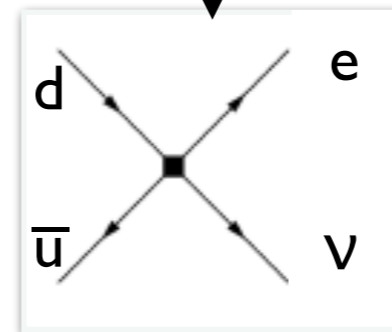
# GeV-scale effective Lagrangian

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$$v = (\sqrt{2}G_F)^{-1/2} \quad \frac{v^2}{\Lambda} \quad (\text{dim-3}) \quad \frac{v}{\Lambda^3} \quad (\text{dim-6})$$

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Pas, Hirsch, Klapdor-  
Kleingrothaus, Kovalenko 1999 \*\*

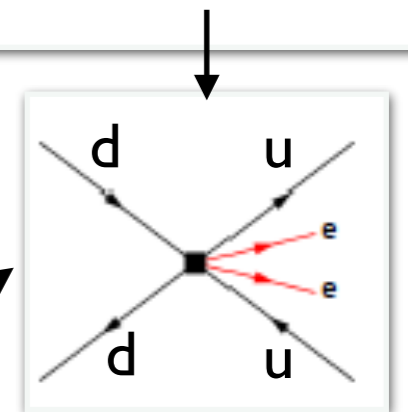
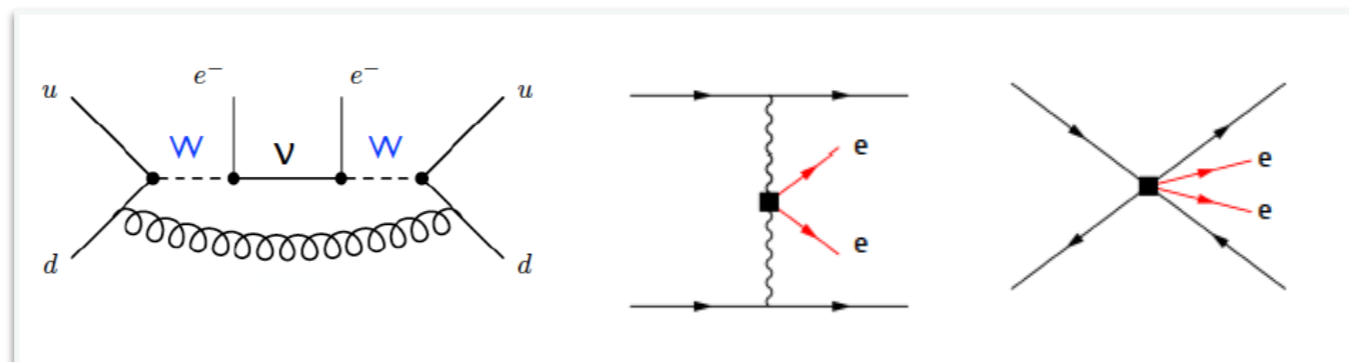


# GeV-scale effective Lagrangian

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$$v = (\sqrt{2}G_F)^{-1/2} \quad \frac{v^2}{\Lambda} \text{ (dim-3)} \quad \frac{v}{\Lambda^3} \text{ (dim-6)} \quad \frac{1}{v^2 \Lambda_\chi^2 \Lambda}, \frac{1}{v^2 \Lambda^3}, \frac{1}{\Lambda^5} \text{ (dim-9)}$$

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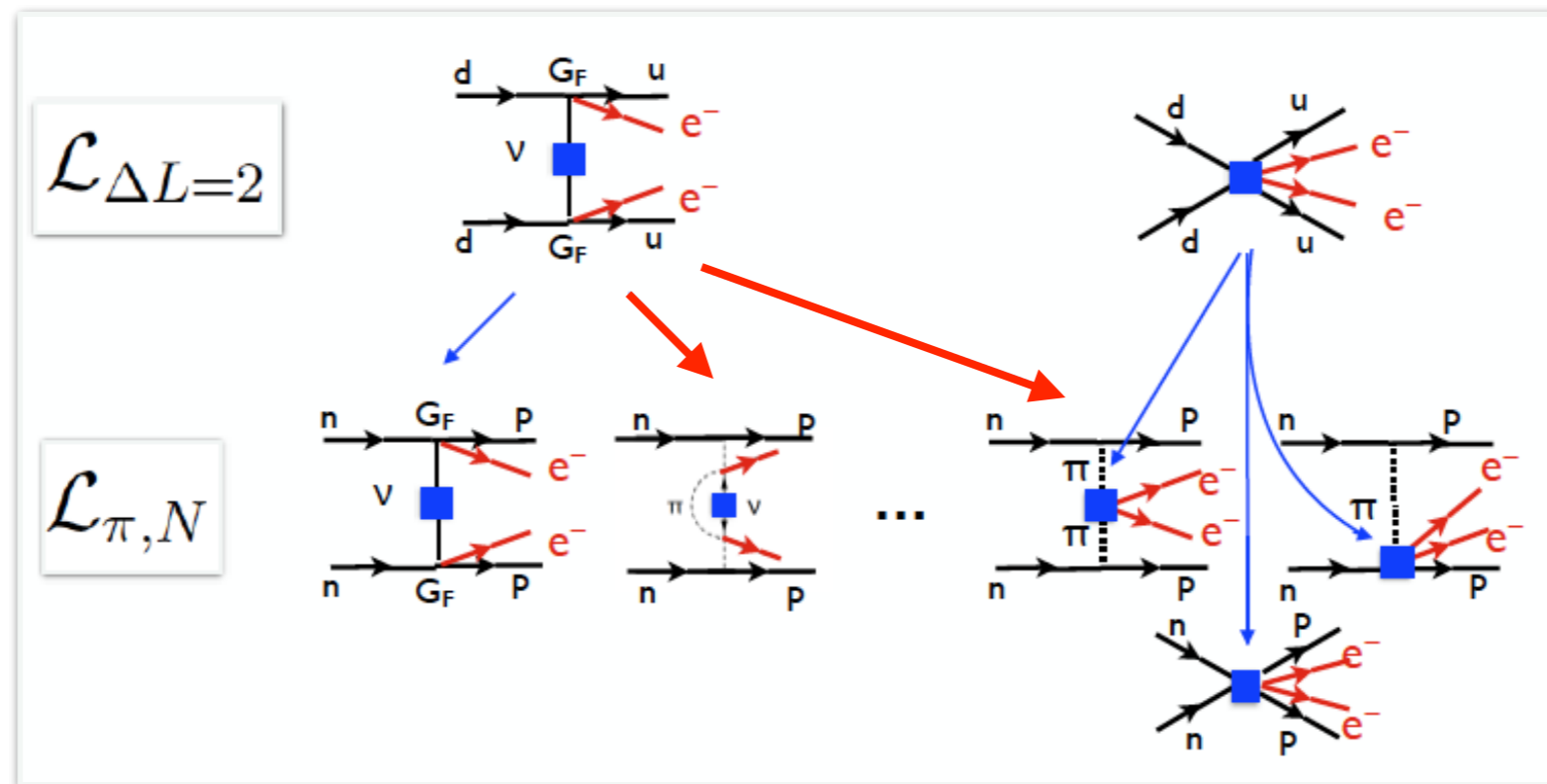
M. Graesser, 1606.04549

Prezeau, Ramsey-Musolf,  
Vogel hep-ph/0303205

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

# From quarks to hadrons

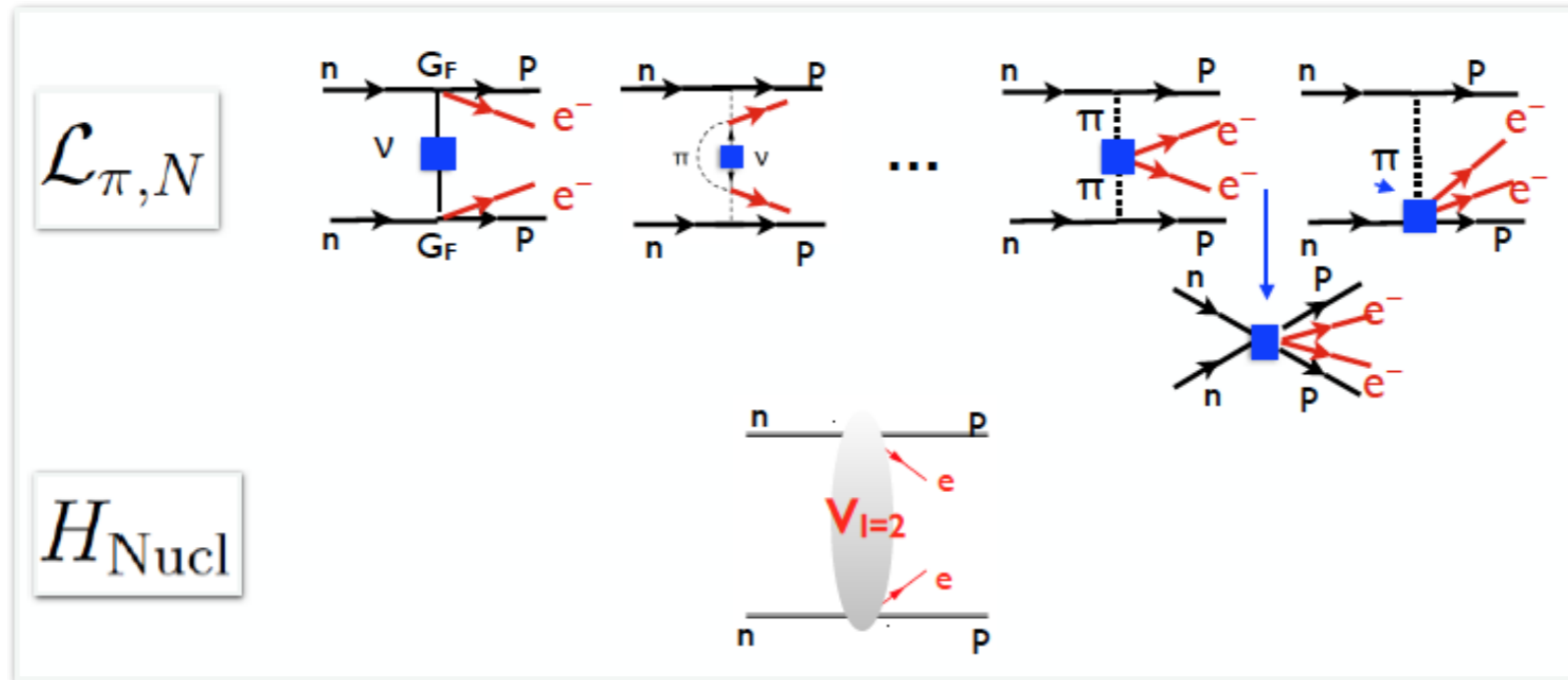
- At  $E \sim \Lambda_\chi \sim m_N \sim \text{GeV}$  map  $\Delta L=2$  Lagrangian onto  $\pi, N$  operators, organized according to power-counting in  $Q/\Lambda_\chi$  ( $Q \sim k_F \sim m_\pi$ )



- \* This step is equivalent to “integrating out” hard neutrinos and gluons ( $E, |\mathbf{p}| > \Lambda_\chi$ )
- \*  $\mathcal{L}_{\pi, N}$  involves hadronic operators with same chiral transformation properties as  $\mathcal{L}_{\Delta L=2}$
- \* Low Energy Constants can be determined by appropriate hadronic matrix elements

# From hadrons to nuclei

- Integrate out  $V$ 's and  $\pi$ 's with  $(E, |\mathbf{p}|) \sim Q$  and  $(E, |\mathbf{p}|) \sim (Q^2/m_N, Q)$

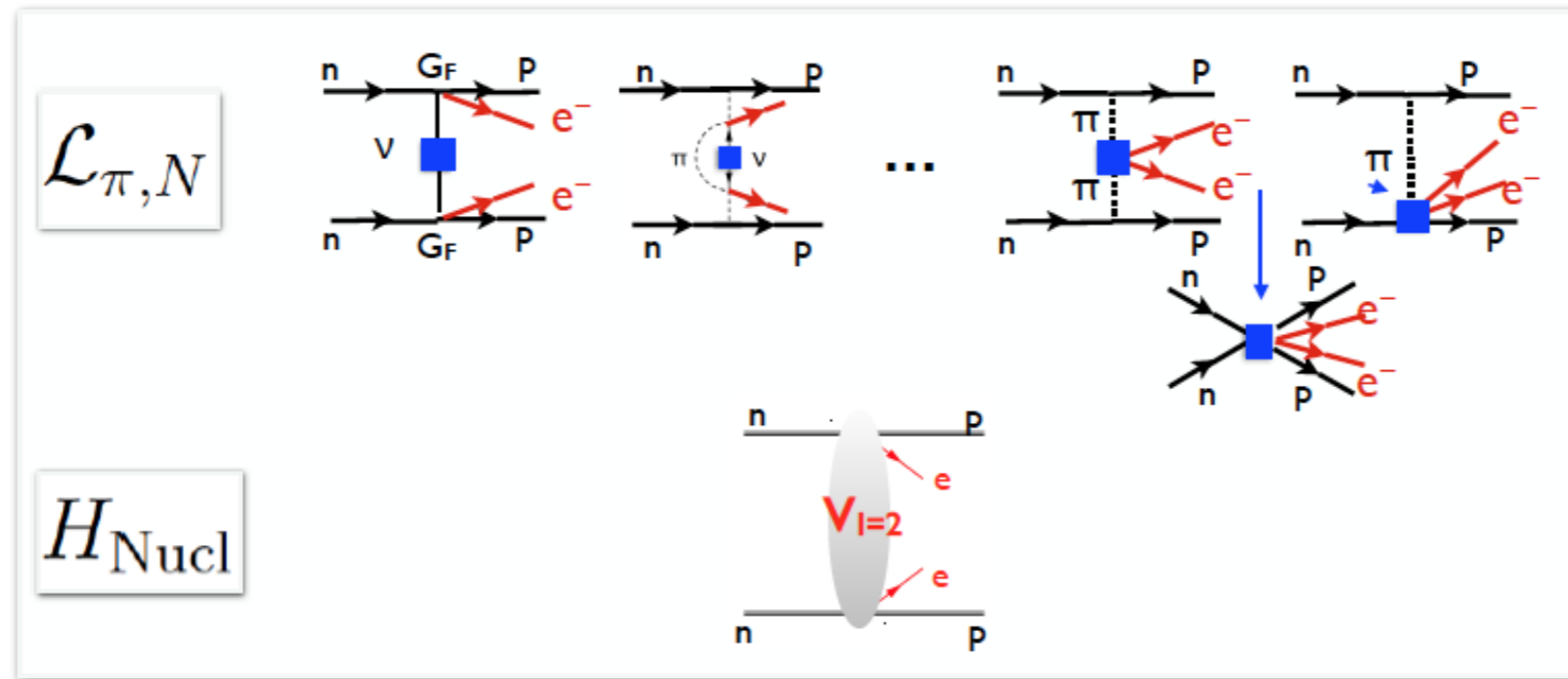


Strong interactions

$$H_{\text{Nucl}} = H_0 + \sqrt{2}G_F V_{ud} \bar{N} (g_V \delta^{\mu 0} - g_A \delta^{\mu i} \sigma^i) \tau^+ N \bar{e}_L \gamma_\mu \nu_L + 2G_F^2 V_{ud}^2 \bar{e}_L e_L^c V_{I=2}$$

# From hadrons to nuclei

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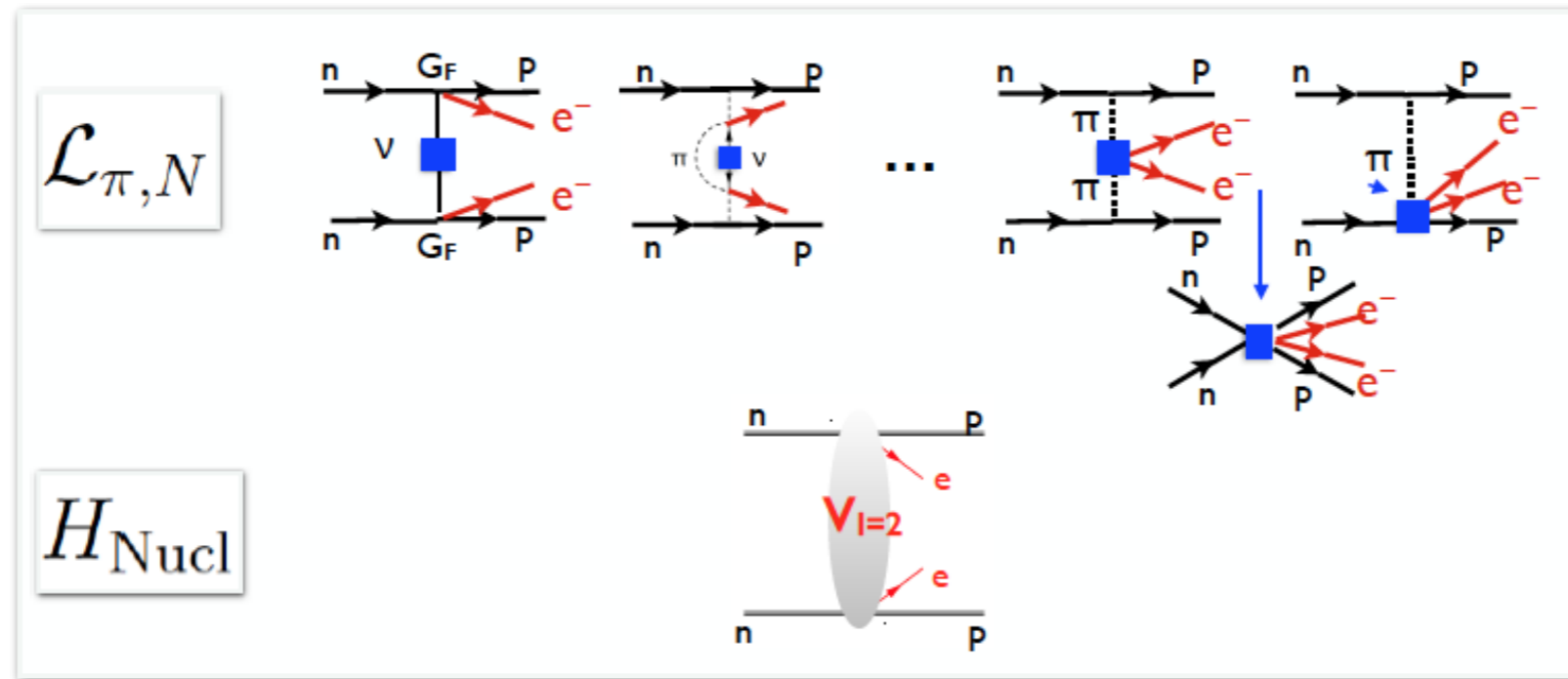
Strong interactions

“Ultra-soft”  $(e, \nu)$  with  $|\mathbf{p}|, E \ll k_F$  cannot be integrated out

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# From hadrons to nuclei

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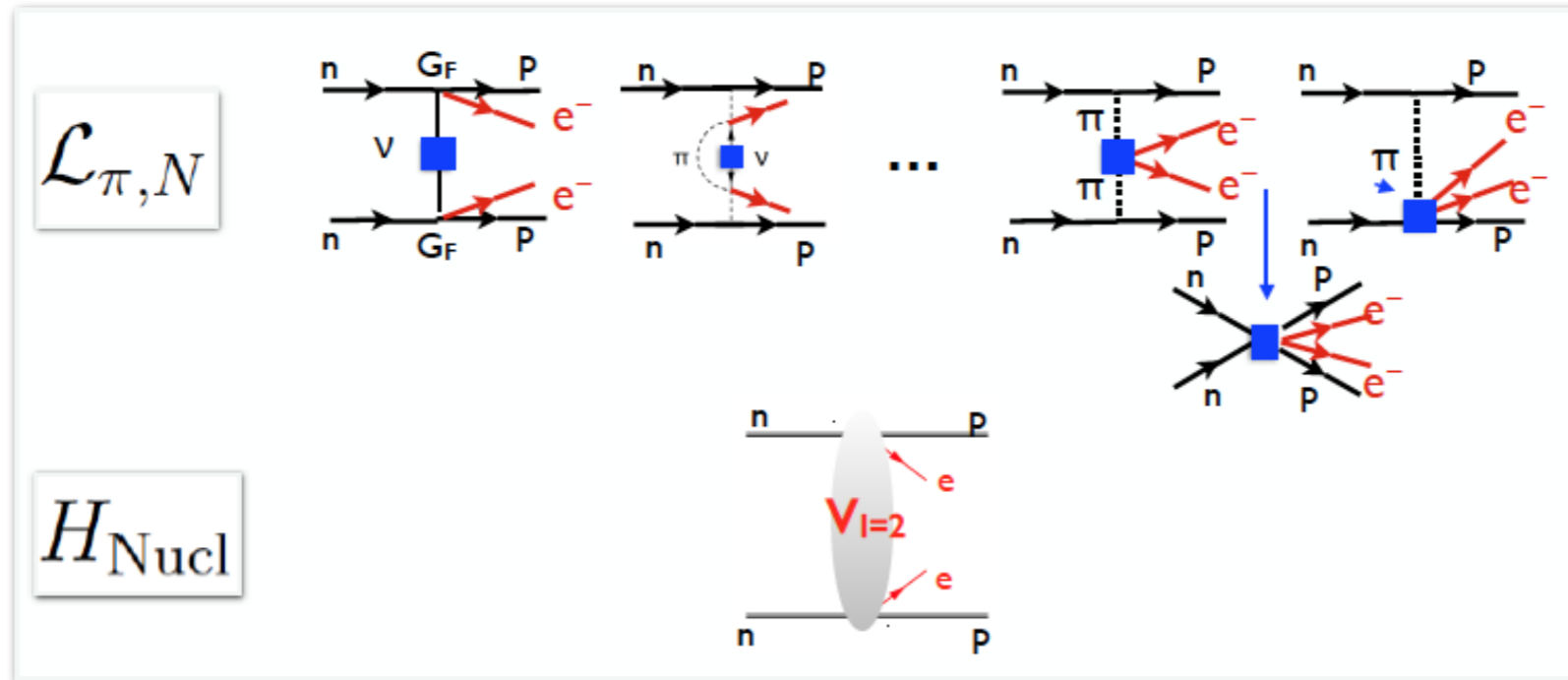
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“Isotensor”  $0\nu\beta\beta$  potential mediates  $nn \rightarrow pp$ .

It can be identified to a given order in  $Q/\Lambda_\chi$  by computing 2-nucleon irreducible diagrams

# From hadrons to nuclei

- Integrate out  $V$ 's and  $\pi$ 's with  $(E, |\mathbf{p}|) \sim Q$  and  $(E, |\mathbf{p}|) \sim (Q^2/m_N, Q)$



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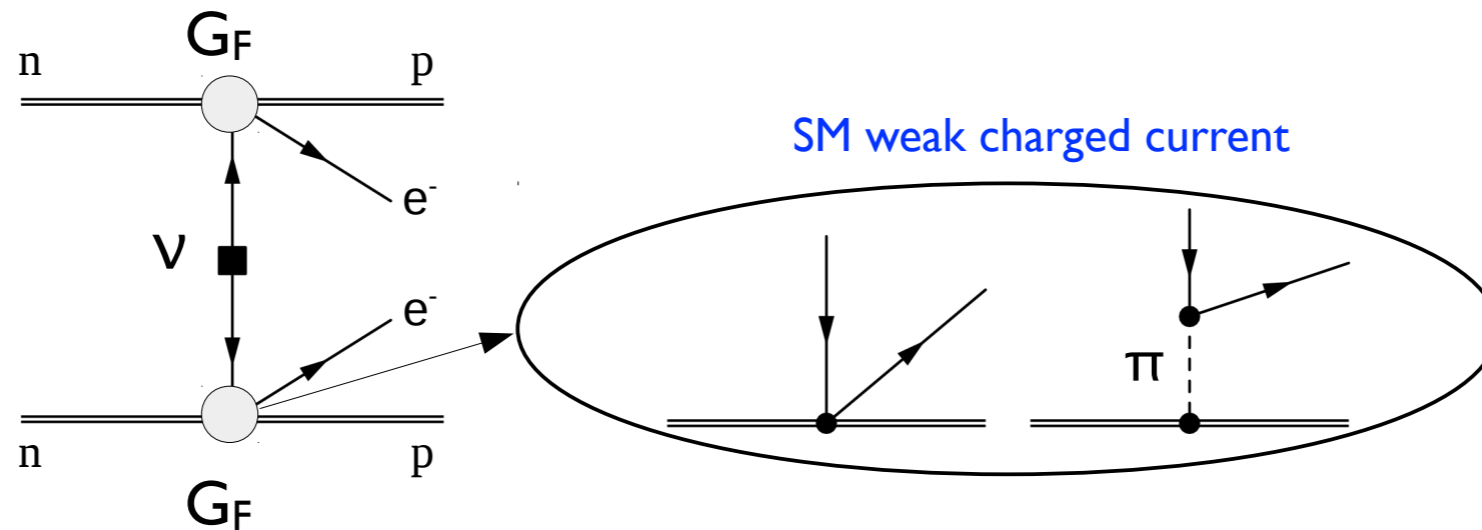
$$V_{I=2} = m_{\beta\beta} V_\nu + \frac{m_\pi^2}{v} (c_{\pi\pi} V_{\pi\pi} + c_{\pi N} V_{\pi N} + c_{NN} V_{NN}) + \dots$$

# $0\nu\beta\beta$ from light Majorana neutrino exchange

V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti, S. Pastore, J. de Vries, U. van Kolck  
(in preparation)

# $0\nu\beta\beta$ potential from light $V_M$

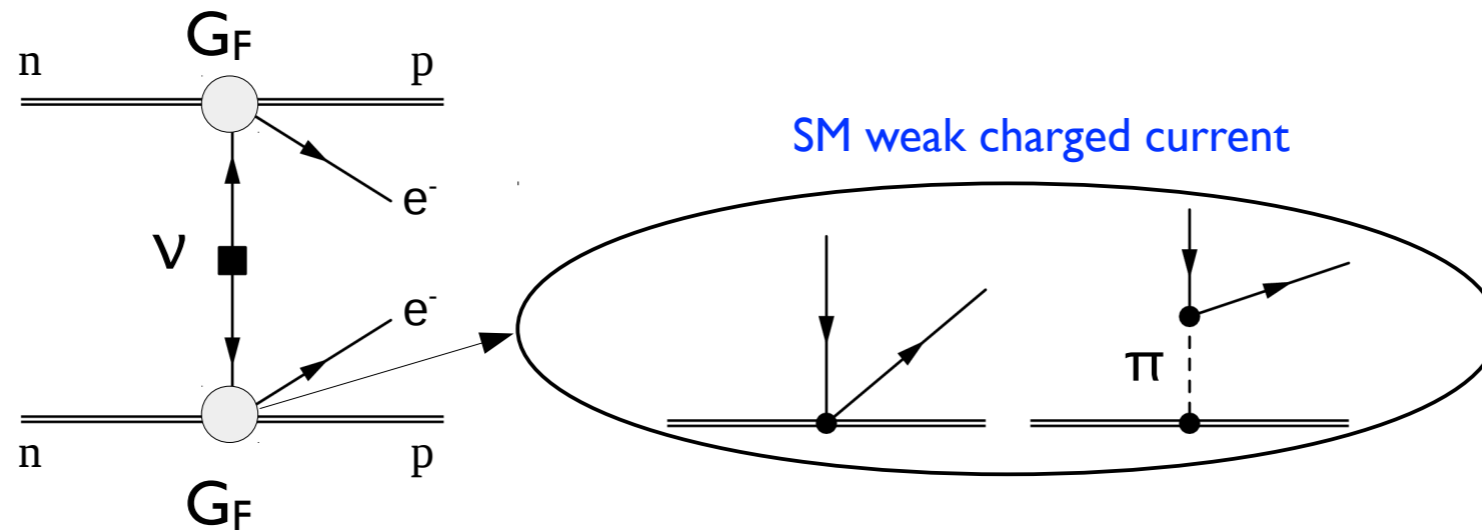


- Leading Order:

$$V_{\nu,0}^{(a,b)} = \tau^{(a)} + \tau^{(b)} + \frac{1}{q^2} \left\{ 1 - g_A^2 \left[ \sigma^{(a)} \cdot \sigma^{(b)} - \sigma^{(a)} \cdot \mathbf{q} \sigma^{(b)} \cdot \mathbf{q} \frac{2m_\pi^2 + q^2}{(q^2 + m_\pi^2)^2} \right] \right\}$$

Hadronic input is  $g_A$

# $0\nu\beta\beta$ potential from light $\nu_M$



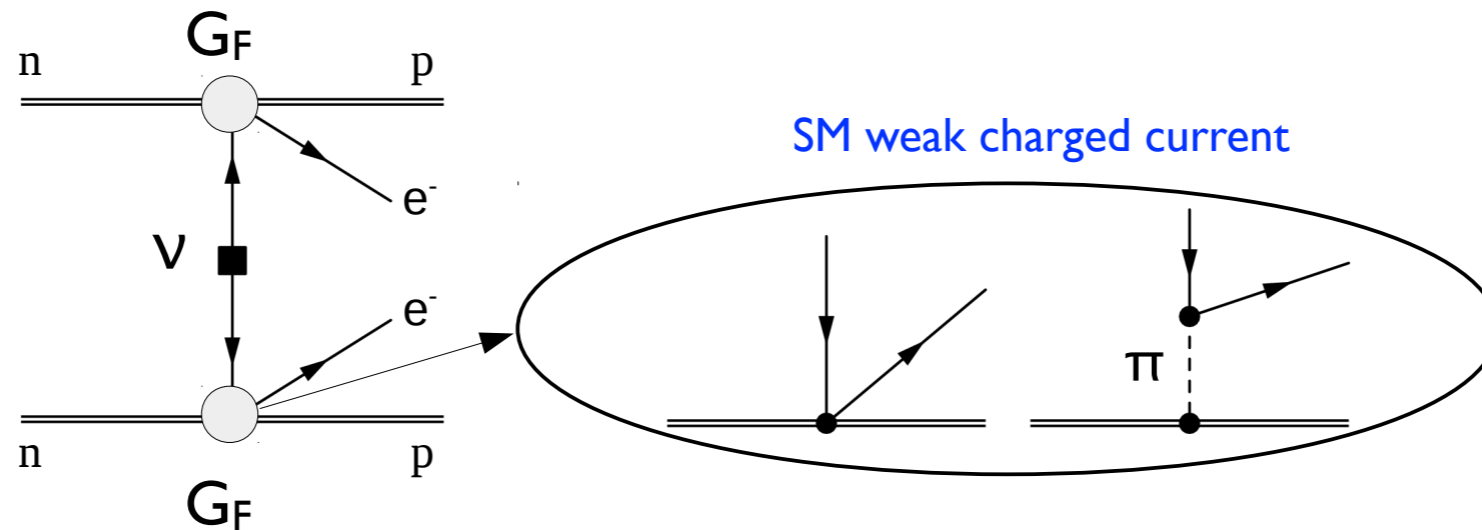
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Hadronic input is  $g_A$

Assume for the moment Weinberg counting  
for contact 4N interactions ( $1/\Lambda_\chi^2$ )

# $0\nu\beta\beta$ potential from light $\nu_M$

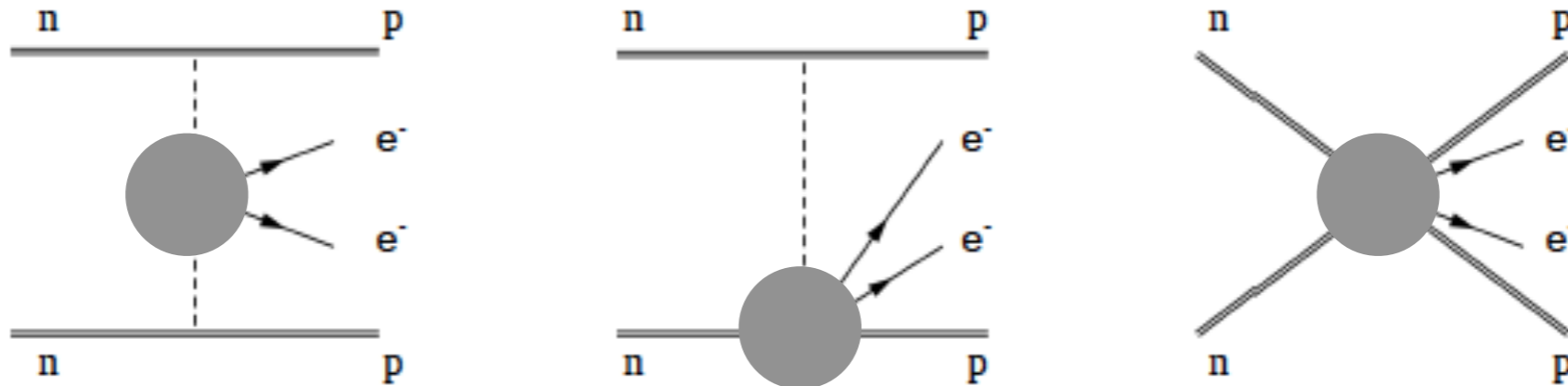
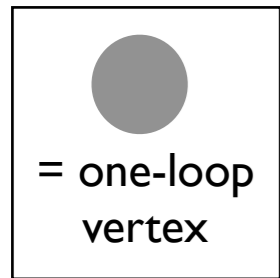


- N<sup>2</sup>LO:

$$V_{\nu,0}^{(a,b)} = \tau^{(a)} + \tau^{(b)} + \frac{1}{q^2} \left\{ 1 - g_A^2 \left[ \sigma^{(a)} \cdot \sigma^{(b)} - \sigma^{(a)} \cdot \mathbf{q} \sigma^{(b)} \cdot \mathbf{q} \frac{2m_\pi^2 + q^2}{(q^2 + m_\pi^2)^2} \right] \right\}$$

- I. Corrections to 1-body currents (radii, magnetic moments, ...) usually taken into account via nucleon form factors

# $0\nu\beta\beta$ potential from light $V_M$



- N<sup>2</sup>LO:

$$V_{\nu,2}^{(a,b)} = \tau^{(a)} + \tau^{(b)} + \left( \mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \log \frac{m_\pi^2}{\mu_{\text{us}}^2} + \mathcal{V}_{CT}^{(a,b)} \right)$$

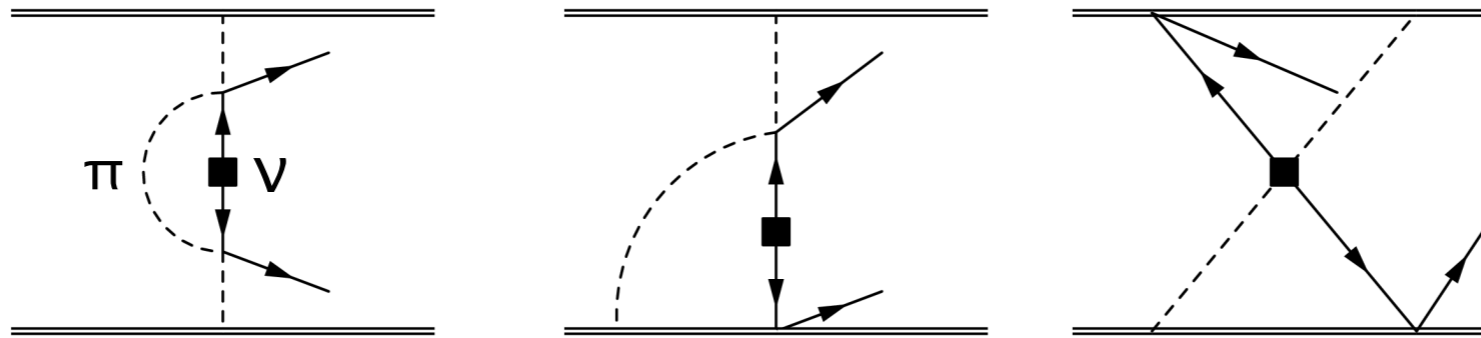
1. Corrections to 1-body currents (radii, magnetic moments, ...) usually taken into account via nucleon form factors

2. Pion loops & local interactions: new, non-factorizable piece

V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

# $0\nu\beta\beta$ potential from light $\nu_M$

Representative  
loop diagrams



- N<sup>2</sup>LO:

$$V_{\nu,2}^{(a,b)} = \tau^{(a)} + \tau^{(b)} + \left( \mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \log \frac{m_\pi^2}{\mu_{\text{us}}^2} + \mathcal{V}_{CT}^{(a,b)} \right)$$

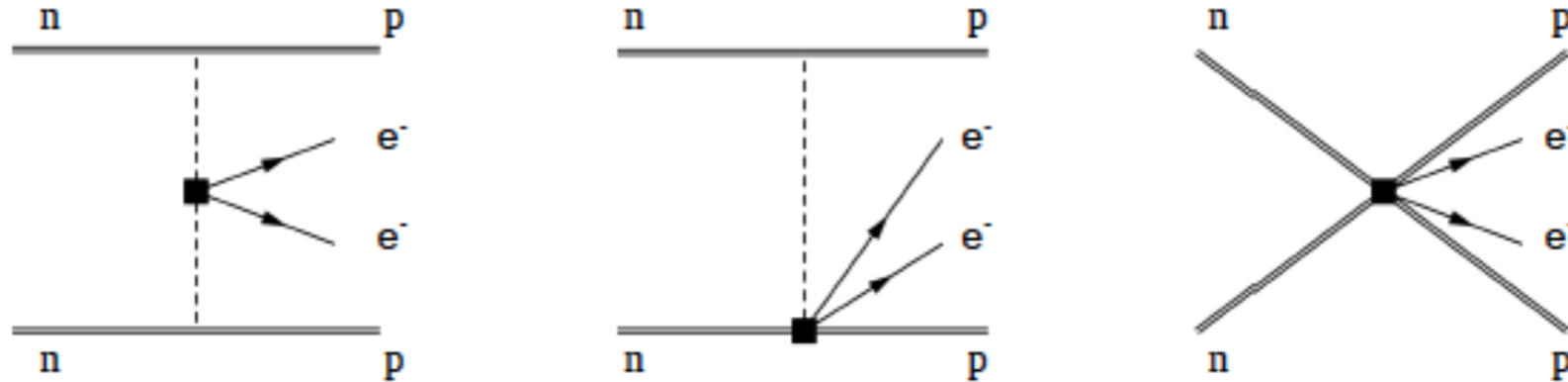
$$\mathcal{V}_{VV}^{(a,b)} = -\frac{g_A^2}{(4\pi F_\pi)^2} \frac{\sigma^{(a)} \cdot \mathbf{q} \sigma^{(b)} \cdot \mathbf{q}}{m_\pi^2} \times \left\{ \frac{2(1 - \hat{q})^2}{\hat{q}^2(1 + \hat{q})} \log(1 + \hat{q}) - \frac{2}{\hat{q}} + \frac{7 - 3\hat{q}L_\pi}{(1 + \hat{q})^2} + \frac{L_\pi}{1 + \hat{q}} \right\}$$

$$\hat{q} = -q^2/m_\pi^2$$

$$L_\pi = \log \frac{\mu^2}{m_\pi^2}.$$

# $0\nu\beta\beta$ potential from light $\nu_M$

Counterterm  
diagrams



- N<sup>2</sup>LO:

$$V_{\nu,2}^{(a,b)} = \tau^{(a)} + \tau^{(b)} + \left( \mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \log \frac{m_\pi^2}{\mu_{\text{us}}^2} + \mathcal{V}_{CT}^{(a,b)} \right)$$

- Loops are UV divergent: need LECs encoding physics at  $E \gtrsim \mu$

$$\mathcal{V}_{CT}^{(a,b)} = \frac{g_A^2}{(4\pi F_\pi)^2} \frac{\boldsymbol{\sigma}^{(a)} \cdot \vec{q} \boldsymbol{\sigma}^{(b)} \cdot \vec{q}}{m_\pi^2} \left[ \frac{5}{6} g_\nu^{\pi\pi} \frac{\hat{q}}{(1 + \hat{q})^2} - g_\nu^{\pi N} \frac{1}{1 + \hat{q}} \right] - g_\nu \mathbf{1}^{(a)} \times \mathbf{1}^{(b)}$$

$g_\nu \sim 1/(4\pi F_\pi)^2$   
in Weinberg counting

# Scaling of contact 4N operators

- We know that Weinberg counting is not consistent for NN scattering
- $m_\pi$  dependence of short-range nuclear force should be  $N^2\text{LO}$

$$\mathcal{L} = -C \bar{N}N\bar{N}N - \frac{m_\pi^2}{(4\pi F_\pi)^2} D_2 \bar{N}N\bar{N}N \quad C, D_2 \sim 1/F_\pi^2$$

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- But UV divergence of the LO amplitude requires promoting it to LO!

Kaplan-Savage-Wise [nucl-th/9605002](https://arxiv.org/abs/nuc1-th/9605002)

$$iA = \text{contact} + \text{box} + \text{higher order} + \dots$$

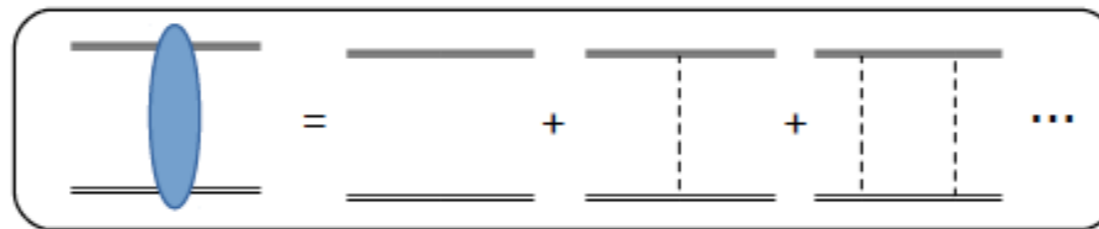
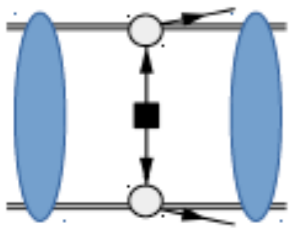
$$= \text{contact} + \frac{\text{box}}{1 - \text{loop}}$$

$$\sim m_\pi^2 C^2 \left( \frac{1}{4-d} + \log \mu^2 \right)$$

# What about contact term in $0\nu\beta\beta$ ?

- Study UV divergences in  $nn \rightarrow ppee$  amplitude, with LO strong potential

$$V_{\text{strong}}(r) = \tilde{C} \delta^{(3)}(\mathbf{r}) + \frac{g_A^2 m_\pi^2}{16\pi F_\pi^2} \frac{e^{-m_\pi r}}{4\pi r}$$

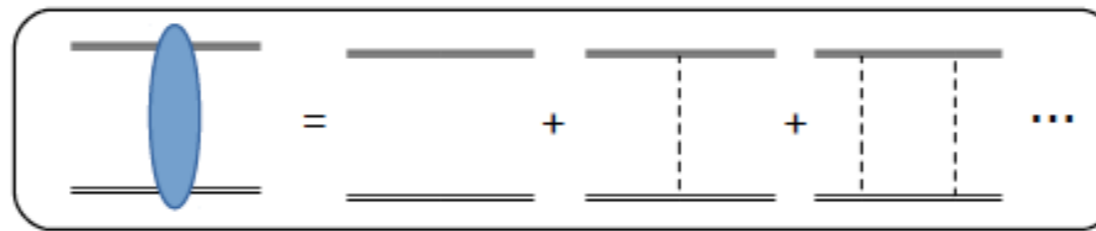
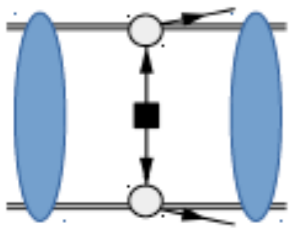


finite

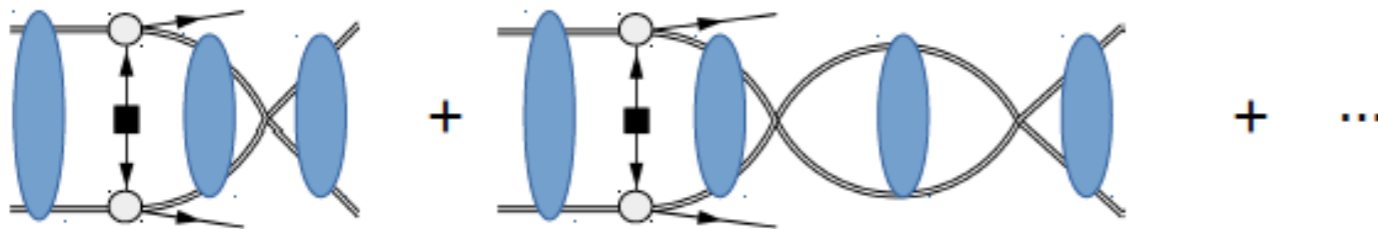
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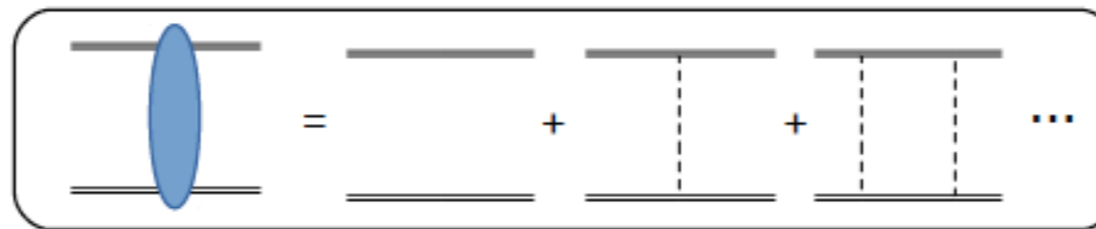
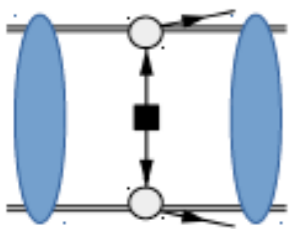


finite

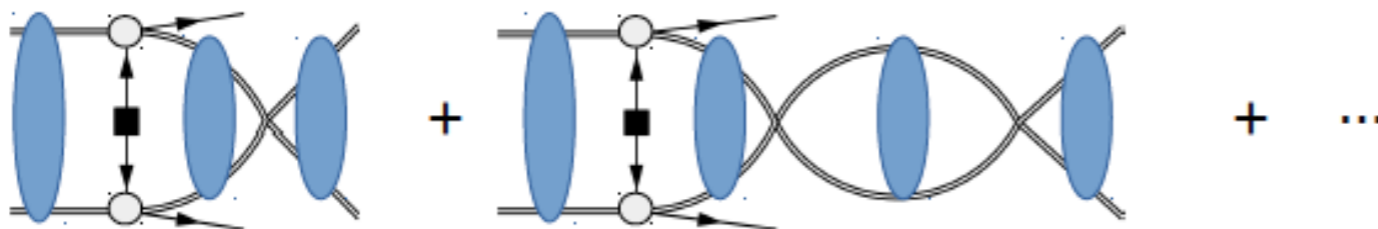
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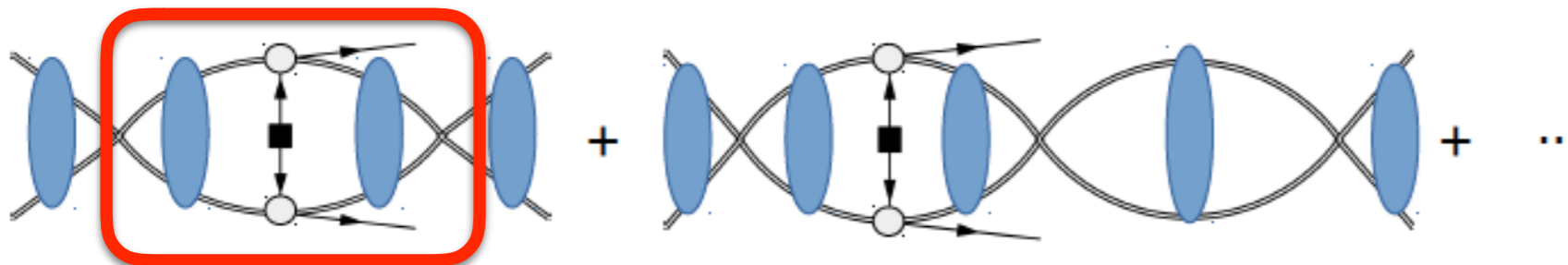
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finite



finite



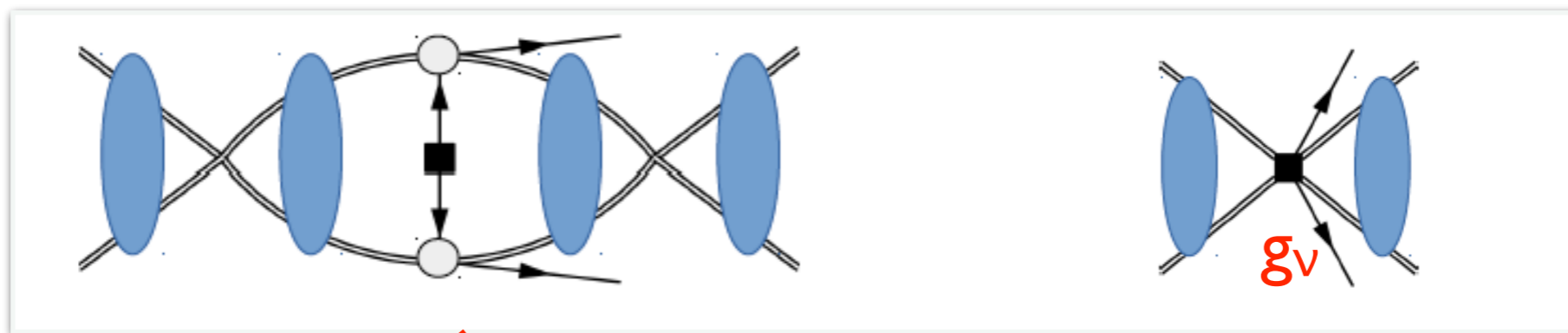
2-loop diagram is  
UV divergent!

# What about contact term in $0\nu\beta\beta$ ?

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- Renormalization requires contact LNV operator at LO!



VC, W. Dekens, M. Graesser, E. Mereghetti, S. Pastore, J. de Vries, U. van Kolck (in preparation)

$$\sim \frac{1}{2}(1 + 2g_A^2) \left( \frac{m_N \tilde{C}}{4\pi} \right)^2 \left( \frac{1}{4-d} + \log \mu^2 \right)$$

- The coupling scales as  $g_v \sim 1/F_\pi^2 \gg 1/(4\pi F_\pi)^2$ , same order as  $1/q^2$  from tree-level neutrino exchange

# If you don't like Feynman diagrams...

- Same conclusion obtained by solving the Schroedinger equation

- Use smeared delta function to regulate short range strong potential

$$\delta^{(3)}(\mathbf{r}) \rightarrow \frac{1}{\pi^{3/2} R_S^3} e^{-\frac{r^2}{R_S^2}}$$

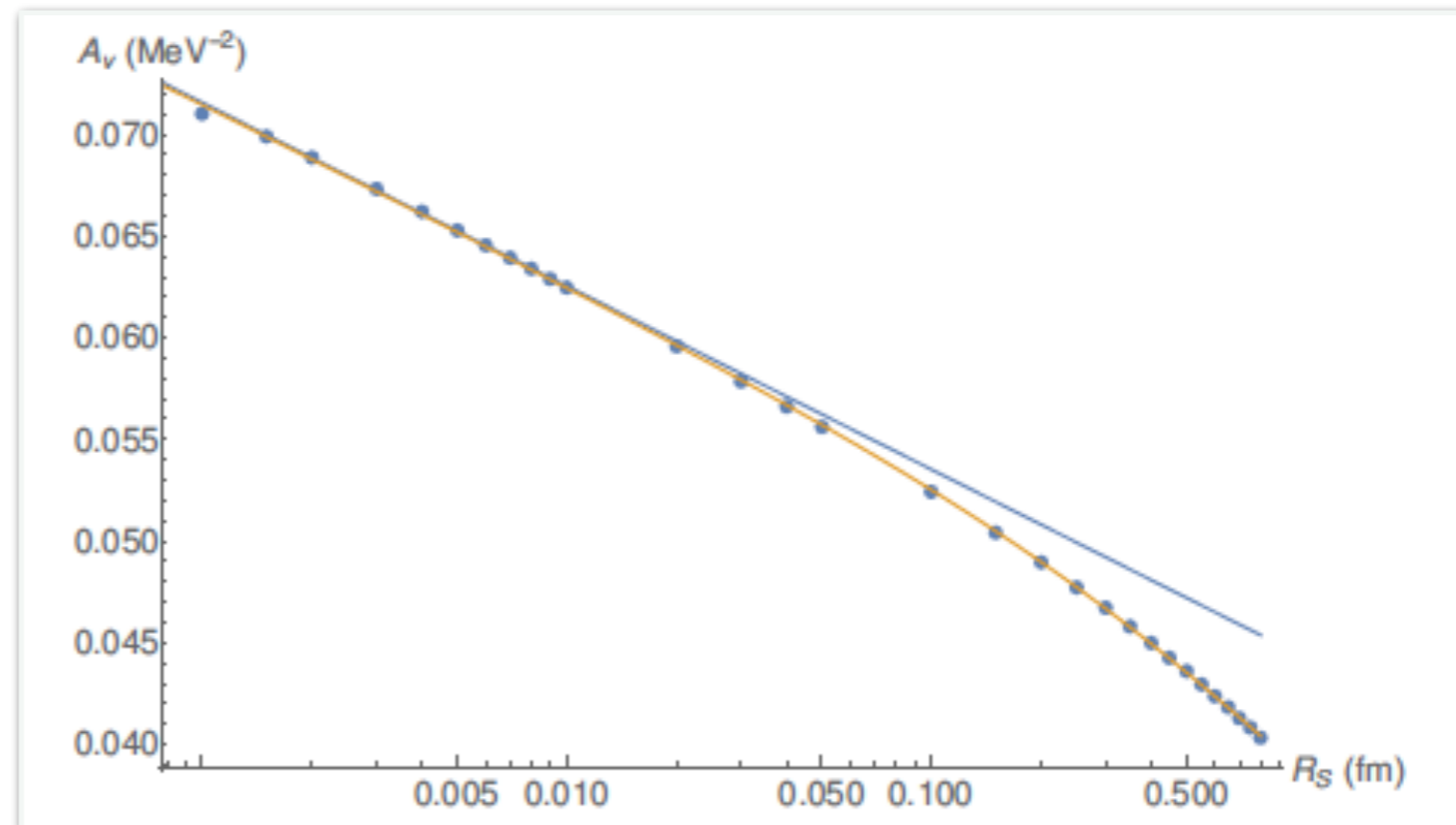
- Compute amplitude

$$\mathcal{A}_\nu = \int d^3\mathbf{r} \psi_{\mathbf{p}'}^-(\mathbf{r}) V_\nu(\mathbf{r}) \psi_{\mathbf{p}}^+(\mathbf{r})$$

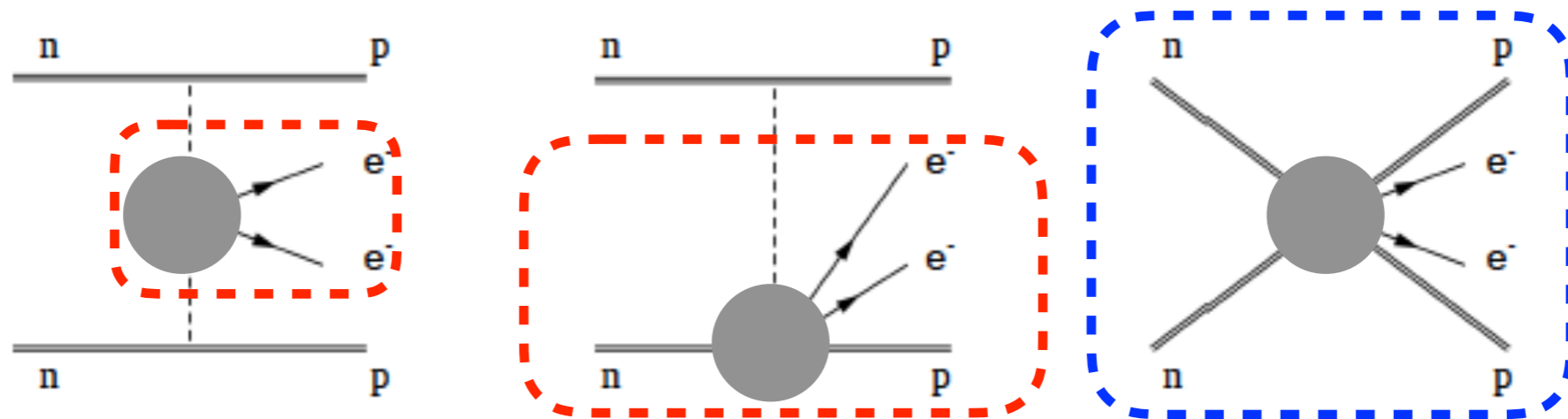
- Logarithmic dependence on  $R_S \Rightarrow$

need LO counterterm

$g_\nu \sim 1/F_\pi^2 \log R_S$  to obtain physical, regulator-independent result



# Estimating the LECs (I)



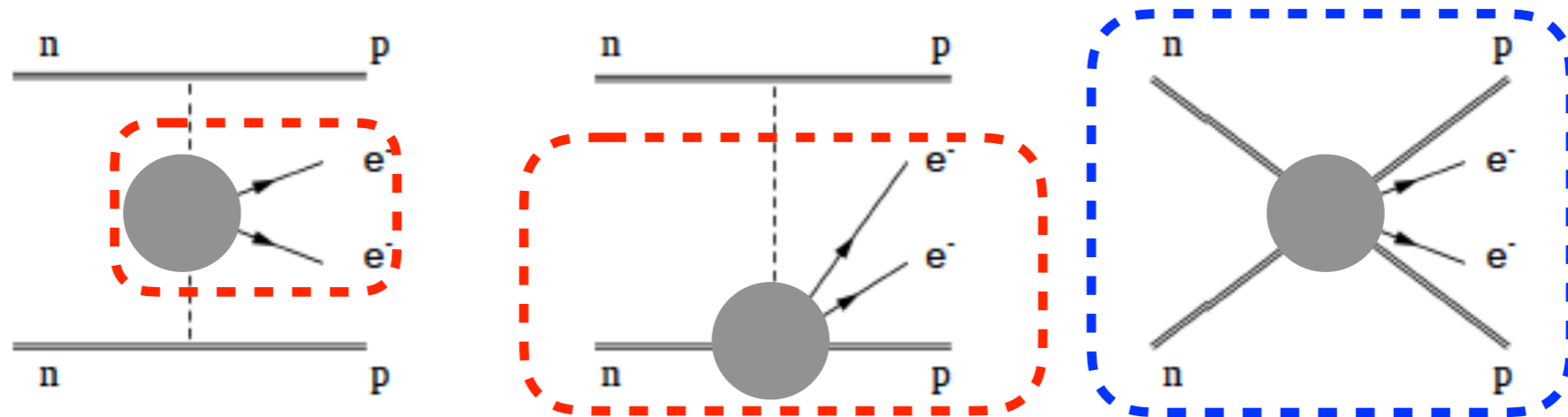
V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- LECs can be fixed by matching  $\chi$ EFT to lattice QCD calculation
- Need to calculate matrix elements of a non-local effective action

$$S_{\text{eff}}^{\Delta L=2} = \frac{8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x d^4y S(x-y) \times \bar{e}_L(x) \gamma^\mu \gamma^\nu e_L^c(y) \times T(\bar{u}_L \gamma_\mu d_L(x) \bar{u}_L \gamma_\mu d_L(y))$$

Scalar massless propagator

# Estimating the LECs (I)



V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- LECs can be fixed by matching  $\chi$ EFT to lattice QCD calculation

$$\langle \pi^+ | S_{\text{NL}} | \pi^- \rangle$$

$$\langle p \pi^+ | S_{\text{NL}} | n \rangle$$

$$\langle pp | S_{\text{NL}} | nn \rangle$$

$$S_{\text{NL}} = \int dx dy S_{\nu}(x - y) T \left( J_{\alpha}^{+}(x) J_{\beta}^{+}(y) \right) g^{\alpha\beta}$$

Scalar massless propagator

$$J_{\alpha}^{+} = \bar{u}_L \gamma_{\alpha} d_L$$

# Estimating the LECs (2)

- LECs can be fixed by relating them to EM LECs (hard  $\gamma$  exchange)

V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

$$\langle e_1 e_2 h_f | S_{\text{eff}}^{\Delta L=2} | h_i \rangle = \frac{8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x \langle e_1 e_2 | \bar{e}_L(x) e_L^c(x) | 0 \rangle \int \frac{d^4k}{(2\pi)^4} \frac{g^{\mu\nu} \hat{\Pi}_{\mu\nu}^{++}(k, x)}{k^2 + i\epsilon},$$
$$\hat{\Pi}_{\mu\nu}^{++}(k, x) = \int d^4r e^{ik \cdot r} \langle h_f | T \left( \bar{u}_L \gamma_\mu d_L(x + r/2) \bar{u}_L \gamma_\nu d_L(x - r/2) \right) | h_i \rangle .$$

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- Neutrino propagator  $\Leftrightarrow$   $\gamma$  propagator in Feynman gauge
- $\Delta L=2$  amplitude related by chiral symmetry to  $I=2$  component of electromagnetic amplitude ( $J_{\text{EM}} \times J_{\text{EM}}$ )

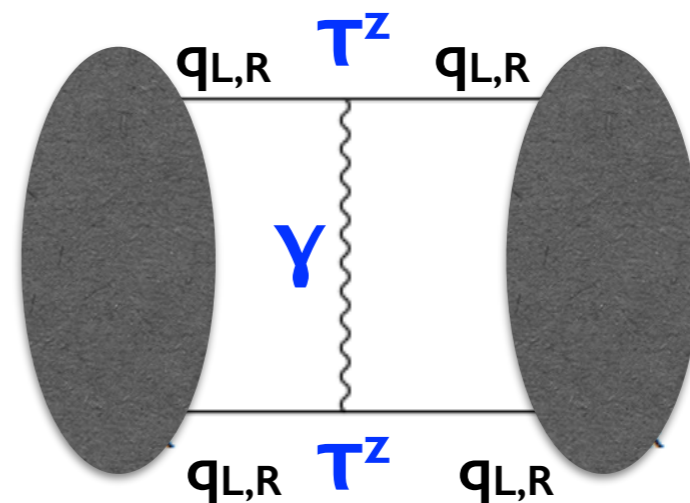
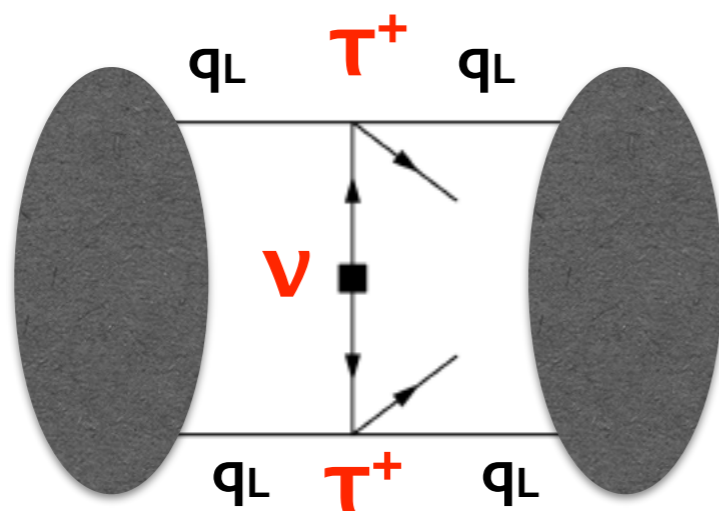
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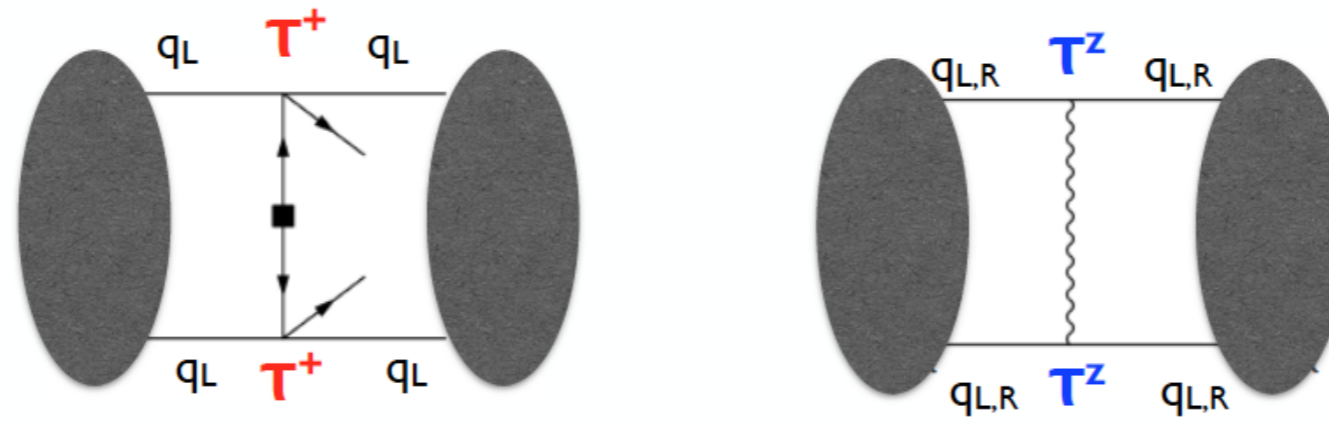
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- Estimates for mesonic ( $\pi\pi$ ) LECs exist!
- Little is known about the  $\pi NN$  coupling
- What about the enhanced 4N couplings?

Ananthanarayan & Moussallam  
hep-ph/0405206

# $0\nu\beta\beta$ vs EM isospin breaking



- Two  $I=2$  operators involving four nucleons

EM case

$$Q_L = \frac{\tau^z}{2}, Q_R = \frac{\tau^z}{2}$$

$$e^2 C_1 \left( \bar{N} Q_L N \bar{N} Q_L N - \frac{\text{Tr}[Q_L^2]}{6} \bar{N} \boldsymbol{\tau} N \cdot \bar{N} \boldsymbol{\tau} N + L \rightarrow R \right)$$

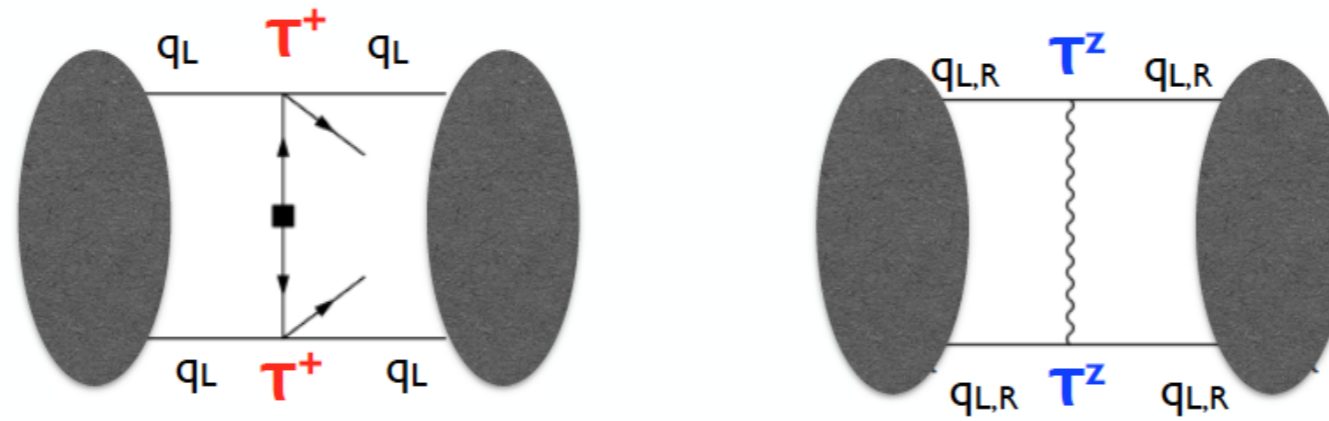
$$e^2 C_2 \left( \bar{N} Q_L N \bar{N} Q_R N - \frac{\text{Tr}[Q_L Q_R]}{6} \bar{N} \boldsymbol{\tau} N \cdot \bar{N} \boldsymbol{\tau} N + L \rightarrow R \right)$$

$$Q_L = u^\dagger Q_L u$$

$$Q_R = u Q_R u^\dagger$$

$$u = 1 + \frac{i\boldsymbol{\pi} \cdot \boldsymbol{\tau}}{2F_\pi} + \dots$$

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$\Delta L=2$  case

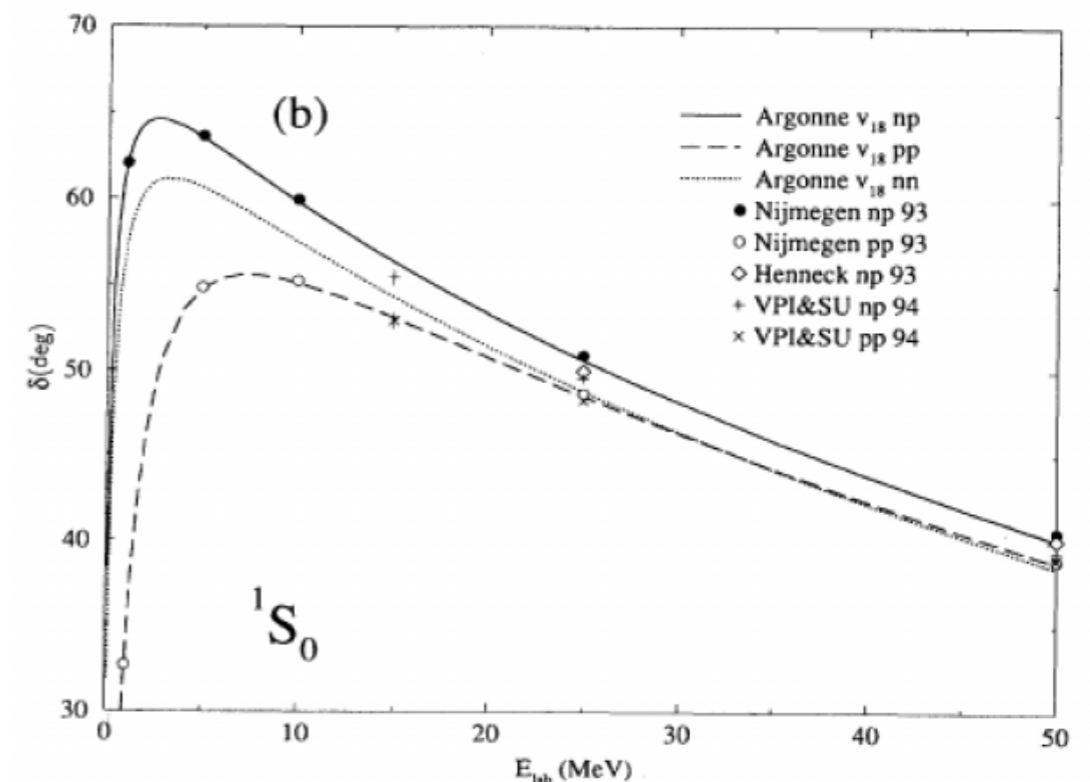
$$Q_L = \tau^+, Q_R = 0$$

$$8G_F^2 V_{ud}^2 m_{\beta\beta} \bar{e}_L e_L^c g_\nu \left( \bar{N} Q_L N \bar{N} Q_L N - \frac{\text{Tr}[Q_L^2]}{6} \bar{N} \tau N \cdot \bar{N} \tau N + L \rightarrow R \right)$$

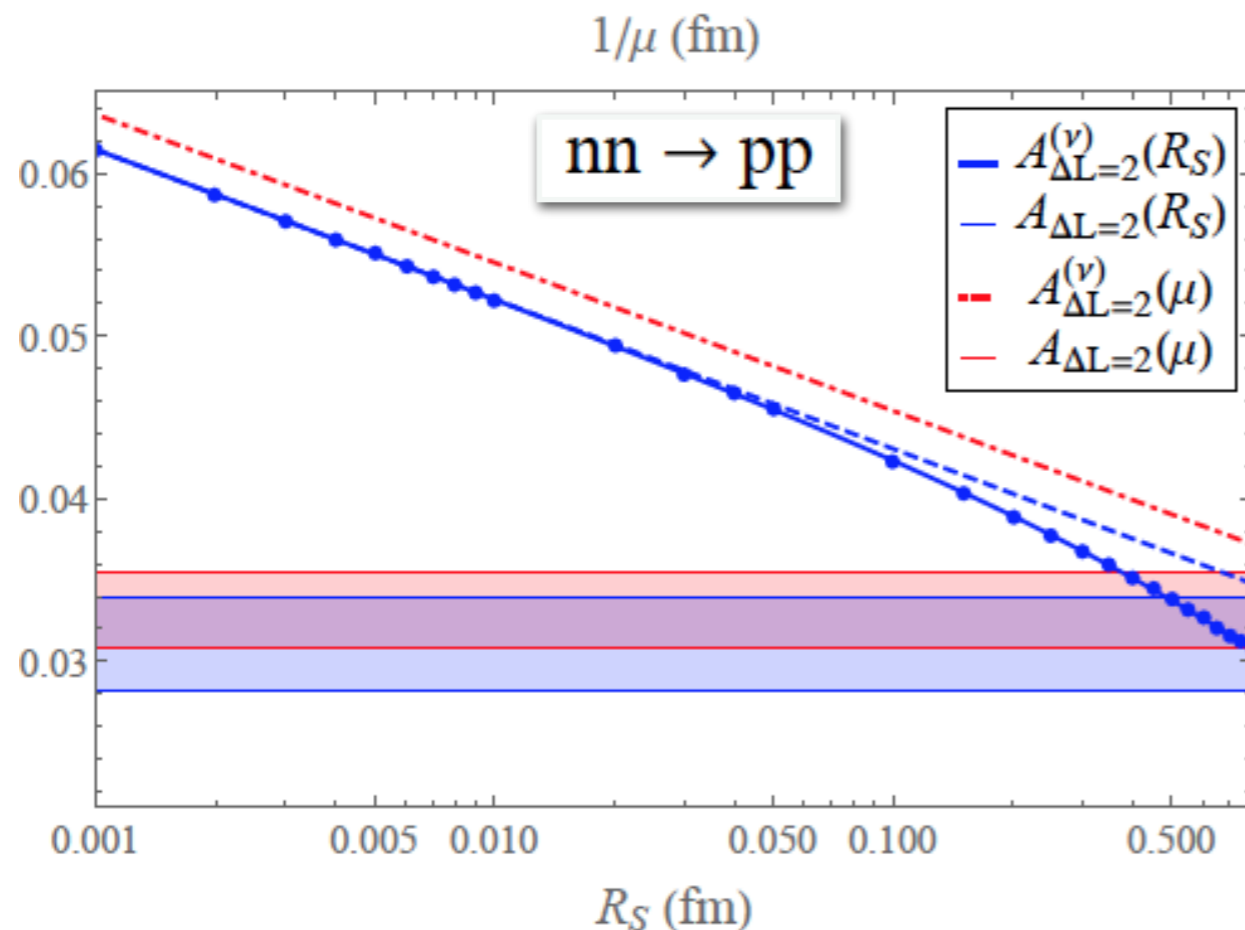
- Chiral symmetry  $\Rightarrow g_\nu = C_1$

# $0\nu\beta\beta$ vs EM isospin breaking

- NN observables cannot disentangle  $C_1$  from  $C_2$  (need pions), but provide data-based estimate of  $g_V$  if  $C_1 \sim C_2$
- $C_1 + C_2$  controls IB combination of  $^1S_0$  scattering lengths  $a_{nn} + a_{pp} - 2 a_{np}$
- Fit to data, including Coulomb potential, pion EM mass splitting, and contact terms confirms that  $C_1 + C_2 \sim 1/F_\pi^2 \gg 1/(4\pi F_\pi)^2$



# Estimating numerical impact



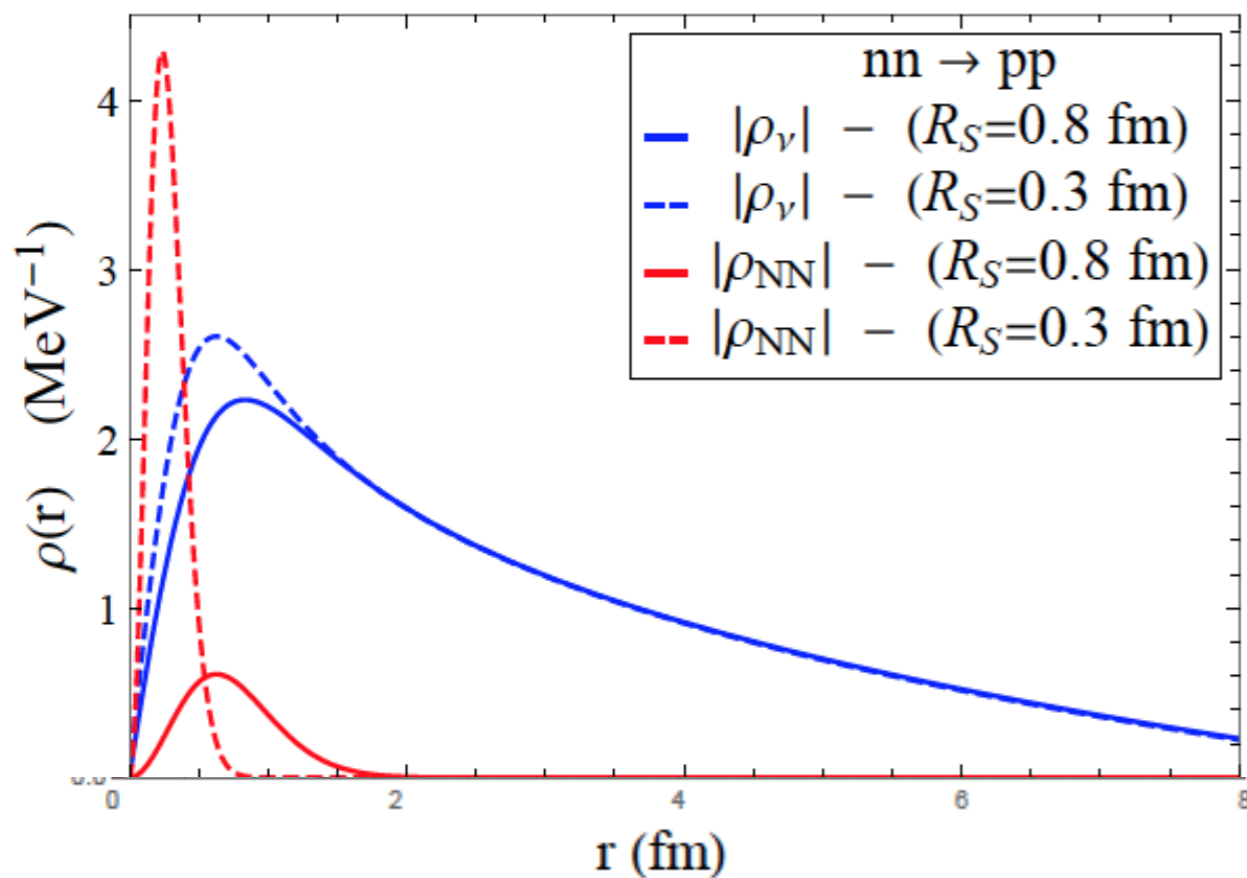
- Assume  $g_v = (C_1 + C_2)/2$  at some scale  $R_S$  between 0.02 and 0.8 fm, with  $C_1 + C_2$  fit to NN data
- $A_{NN} + A_v$  is  $R_S$  (or  $\mu$ ) independent
- $A_{NN}/A_v \sim 10\%$  (30%) at  $R_S \sim 0.8$  fm (0.3 fm) \*\*
- \*\* Actual correction might be different because  $C_1 \neq C_2$

# Estimating numerical impact

$$A = \int dr \rho(r)$$

nn  $\rightarrow$  pp

$\Delta I=0$



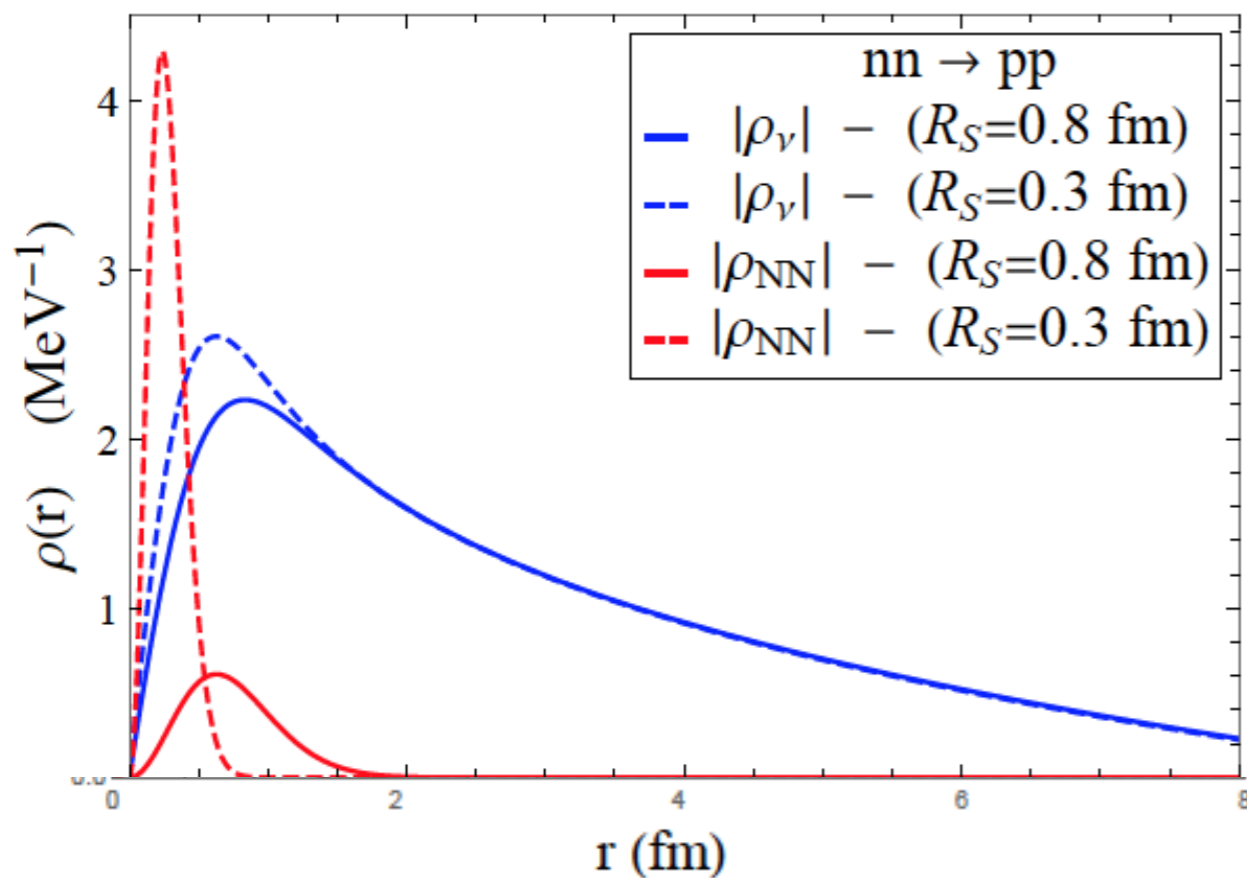
- Anatomy of this result: look at “matrix-element density” as function of inter-nucleon distance

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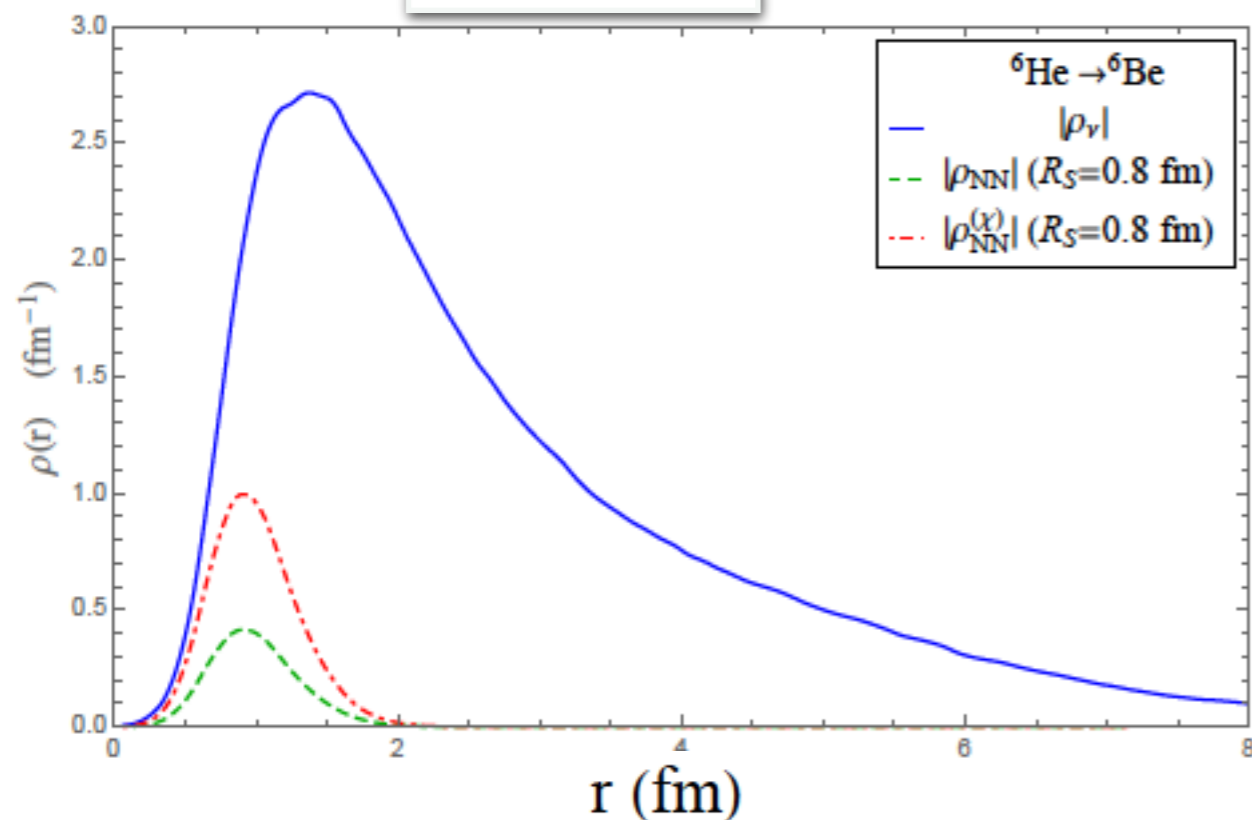


- Anatomy of this result: look at “matrix-element density” as function of inter-nucleon distance
- What about nuclei?
- We explored the impact on light nuclei with wavefunctions obtained via Variational Monte Carlo from AV18 (NN) + U9 (NNN) potentials

# Estimating numerical impact

$$A = \int dr \rho(r)$$

${}^6\text{He} \rightarrow {}^6\text{Be}$   $\Delta I=0$



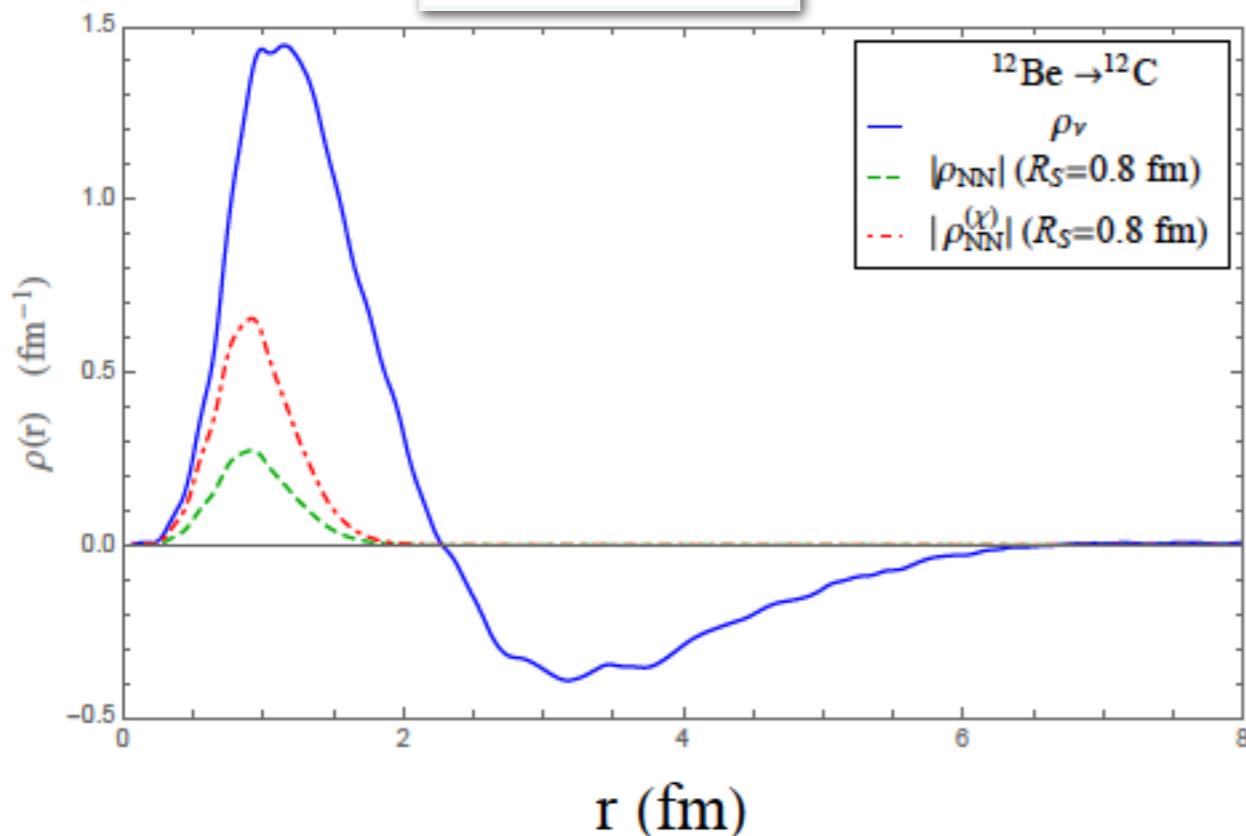
For  $\Delta I=0$  transitions  
situation is similar to  
 $nn \rightarrow pp$  case

- Hybrid calculation at this stage: can't expect  $R_S$ -independence
- $g_v \sim (C_1 + C_2)/2$  taken from fit to NN data (ours vs Piarulli et al. [1606.06335](#))

# Estimating numerical impact

$$A = \int dr \rho(r)$$

$^{12}\text{Be} \rightarrow ^{12}\text{C}$   $\Delta I=2$

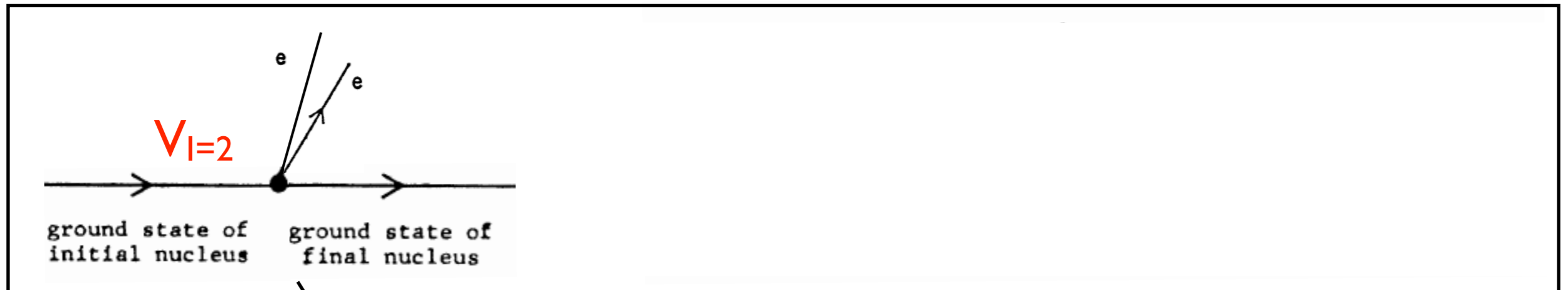


$g_v$  contribution sizable in  $\Delta I=2$  transition (due to node):  
for  $A=12$ ,  $A_{NN}/A_v = 25\%-55\%$

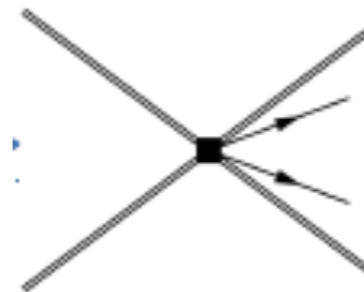
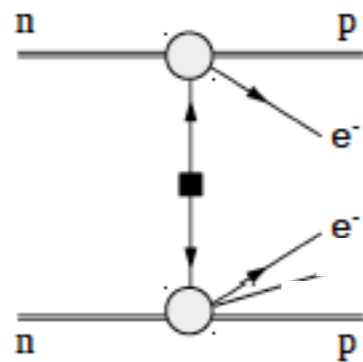
Transitions of experimental interest ( $^{76}\text{Ge} \rightarrow ^{76}\text{Se}, \dots$ ) have  $\Delta I=2$   
 $\Rightarrow m_{\beta\beta}$  phenomenology can be significantly affected!

# $0\nu\beta\beta$ amplitude summary

Figure adapted from Primakoff-Rosen 1969



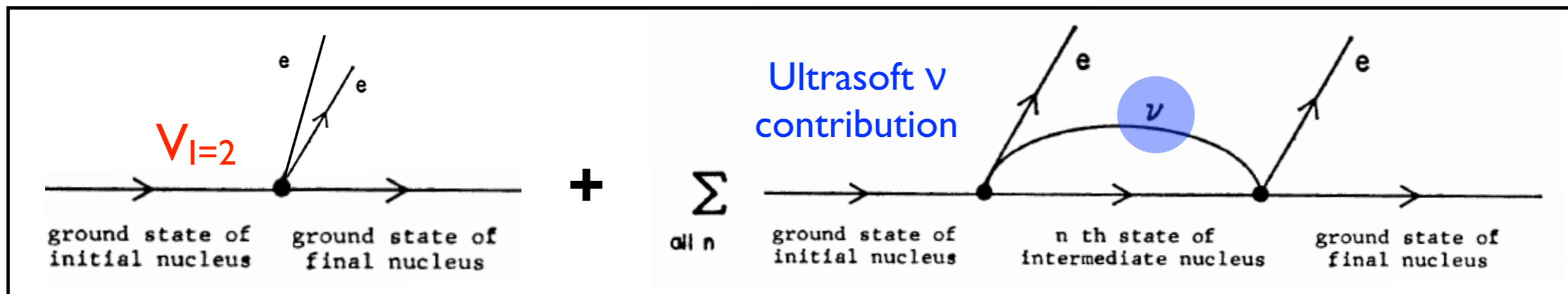
- Leading amplitude controlled by *ground state* matrix element of  $V_{\nu,0}$



New short range contribution

# $0\nu\beta\beta$ amplitude summary

Figure adapted from Primakoff-Rosen 1969



- N2LO amplitude:

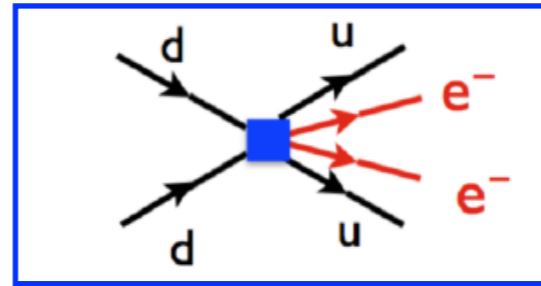
- Factorizable corrections to 1-body currents (radii,, ...)
- Ground state matrix element of  $V_{V,2} \sim V_{V,0} (k_F/4\pi F_\pi)^2$  (involving new non-factorizable effects)
- Ultrasoft neutrino contribution suppressed by  $(E_n - E_i)/(4\pi k_F)$

# $0\nu\beta\beta$ from short distance mechanisms

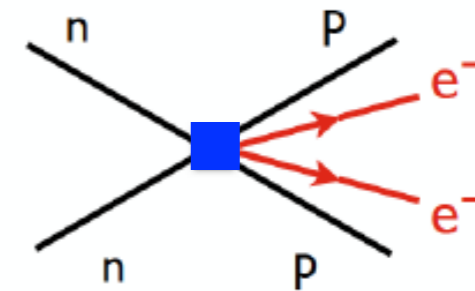
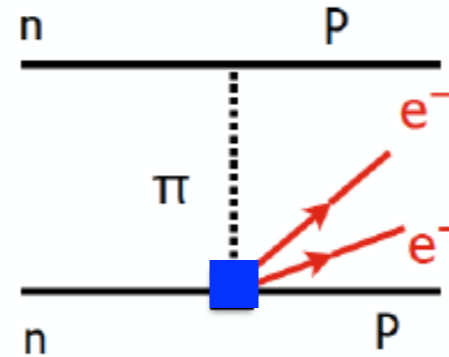
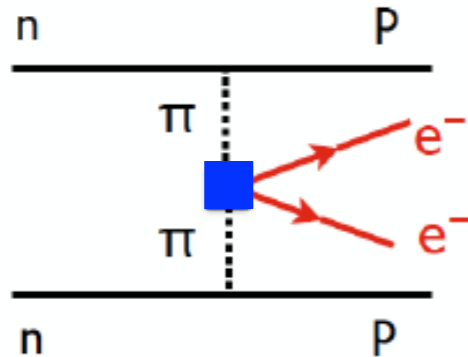
V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti 1701.01443

# $0\nu\beta\beta$ from $\mathcal{L}^{(9)}_{\Delta L=2}$

Pion-range  
effects



Short-range  
effects



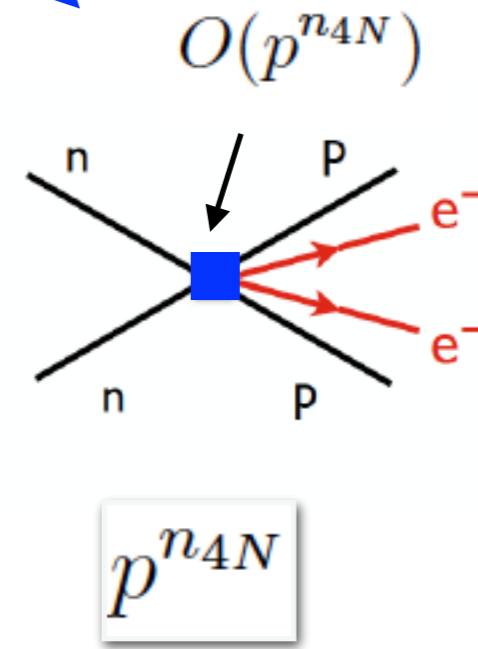
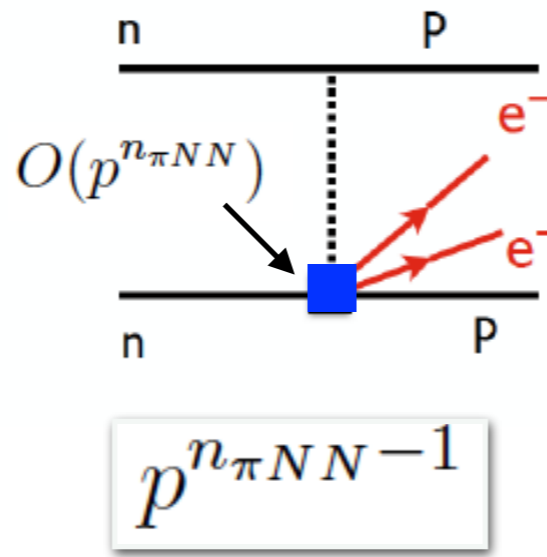
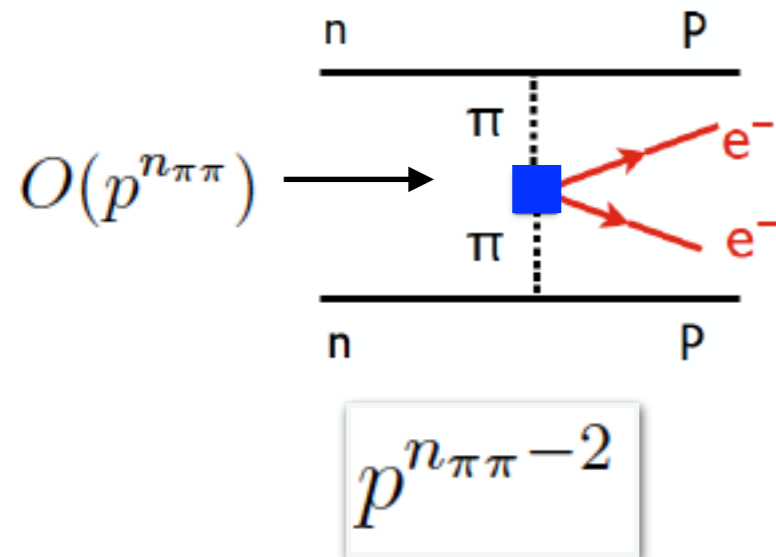
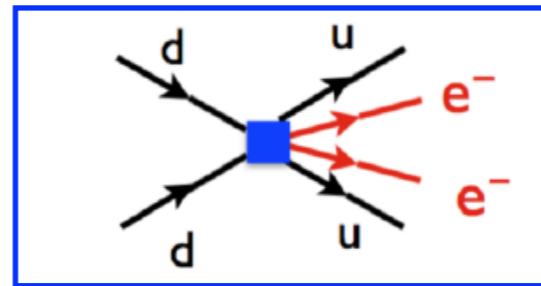
$$V_{I=2} \supset (c_{\pi\pi} V_{\pi\pi} + c_{\pi N} V_{\pi N} + c_{NN} V_{NN})$$

$c_\alpha \sim$  short-distance coupling (model-dep.)  $\times$  **hadronic matrix element**

# $0\nu\beta\beta$ from $\mathcal{L}_{\Delta L=2}^{(9)}$

Pion-range effects

Short-range effects



$$p \sim Q/\Lambda_\chi$$

- Relative importance of  $V_{\pi\pi, \pi N, NN}$  depends on  $O_i$ 's chiral properties: in Weinberg's counting, **2-pion exchange dominates if  $n_{\pi\pi}=0$**
- **Needed hadronic m.e.:  $\langle \pi^+ | O_i | \pi^- \rangle$ ,  $\langle p \pi^+ | O_i | n \rangle$ ,  $\langle pp | O_i | nn \rangle$**

# Scalar operators in $\mathcal{L}_{\Delta L=2}^{(9)}$

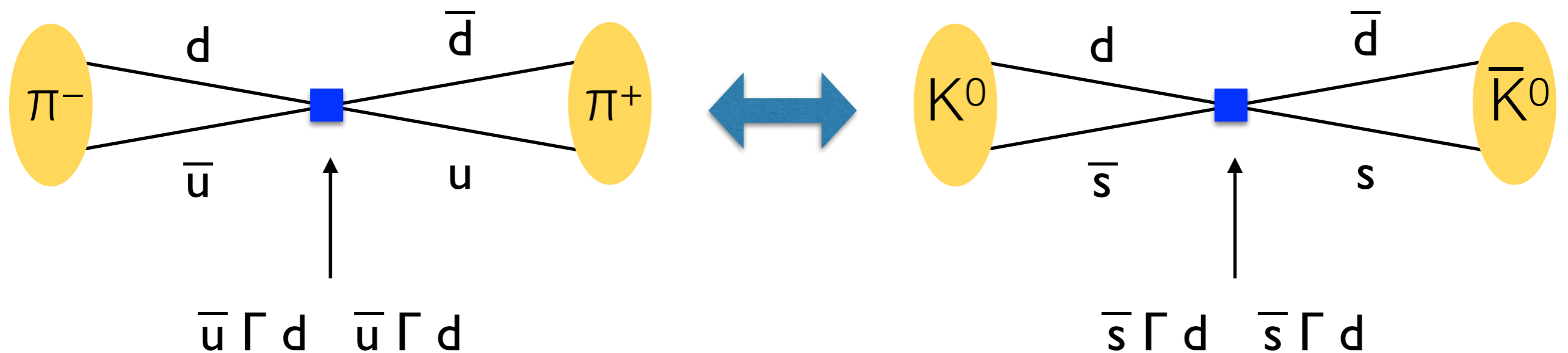
OPERATOR	SU(3) <sub>L</sub> × SU(3) <sub>R</sub> IRREP
$\mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \bar{u}_L \gamma_\mu d_L$	$(\mathbf{27}_L, \mathbf{1}_R)$
$\mathcal{O}_{2,3} = \bar{u}_L d_R \bar{u}_L d_R$	$(\bar{\mathbf{6}}_L, \mathbf{6}_R)$
$\mathcal{O}_{4,5} = \bar{u}_L \gamma^\mu d_L \bar{u}_R \gamma_\mu d_R$	$(\mathbf{8}_L, \mathbf{8}_R)$

- Two ways to obtain  $\langle \pi^+ | \mathcal{O}_i | \pi^- \rangle$ :
  - Direct LQCD calculation (CalLat) Nicholson et al., 1608.04793
  - Indirect LQCD calculation:  $K-\bar{K}$  + chiral SU(3)

V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti 1701.01443, PLB 769 (2017) 460-464

# $\langle \pi^+ | O_i | \pi^- \rangle$ from Kaon physics

- Chiral SU(3) relates  $\langle \pi^+ | O_i | \pi^- \rangle$  to  $\langle \bar{K}^0 | O_i^{(X)} | K^0 \rangle$

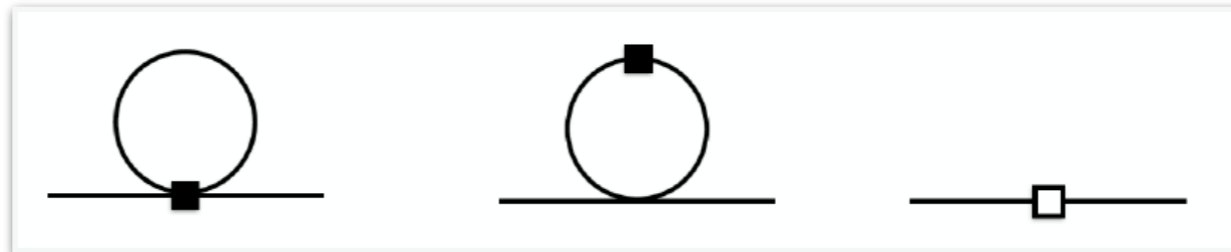


Equal in the SU(3) symmetry limit

# $\langle \pi^+ | O_i | \pi^- \rangle$ from Kaon physics

- Chiral SU(3) relates  $\langle \pi^+ | O_i | \pi^- \rangle$  to  $\langle \bar{K}^0 | O_i^{(X)} | K^0 \rangle$

- Chiral corrections



- Input:  $K$ - $\bar{K}$  matrix elements at  $\mu = 3$  GeV in  $\overline{\text{MS}}$  scheme

Aoki et al.,  
1607.00299

V. Cirigliano, W. Dekens, M. Graesser, E. Mereghetti 1701.01443, PLB 769 (2017) 460-464

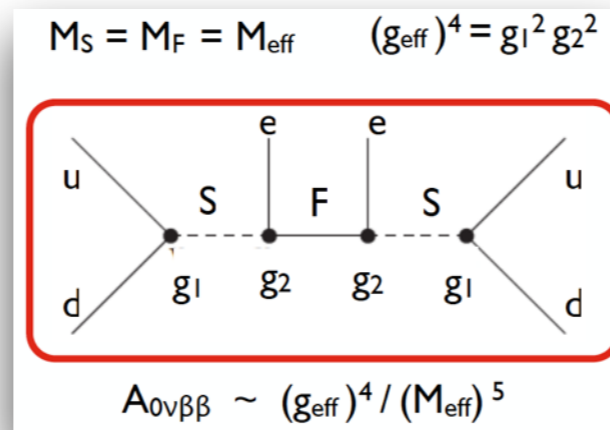
$\langle \pi^+   O_1   \pi^- \rangle$	$=$	$(1.0 \pm 0.1 \pm 0.2) \times 10^{-4} \text{ GeV}^4$
$\langle \pi^+   O_2   \pi^- \rangle$	$=$	$-(2.7 \pm 0.3 \pm 0.5) \times 10^{-2} \text{ GeV}^4$
$\langle \pi^+   O_3   \pi^- \rangle$	$=$	$(0.9 \pm 0.1 \pm 0.2) \times 10^{-2} \text{ GeV}^4$
$\langle \pi^+   O_4   \pi^- \rangle$	$=$	$-(2.6 \pm 0.8 \pm 0.8) \times 10^{-2} \text{ GeV}^4$
$\langle \pi^+   O_5   \pi^- \rangle$	$=$	$-(11 \pm 2 \pm 3) \times 10^{-2} \text{ GeV}^4$

First error:  
lattice QCD input

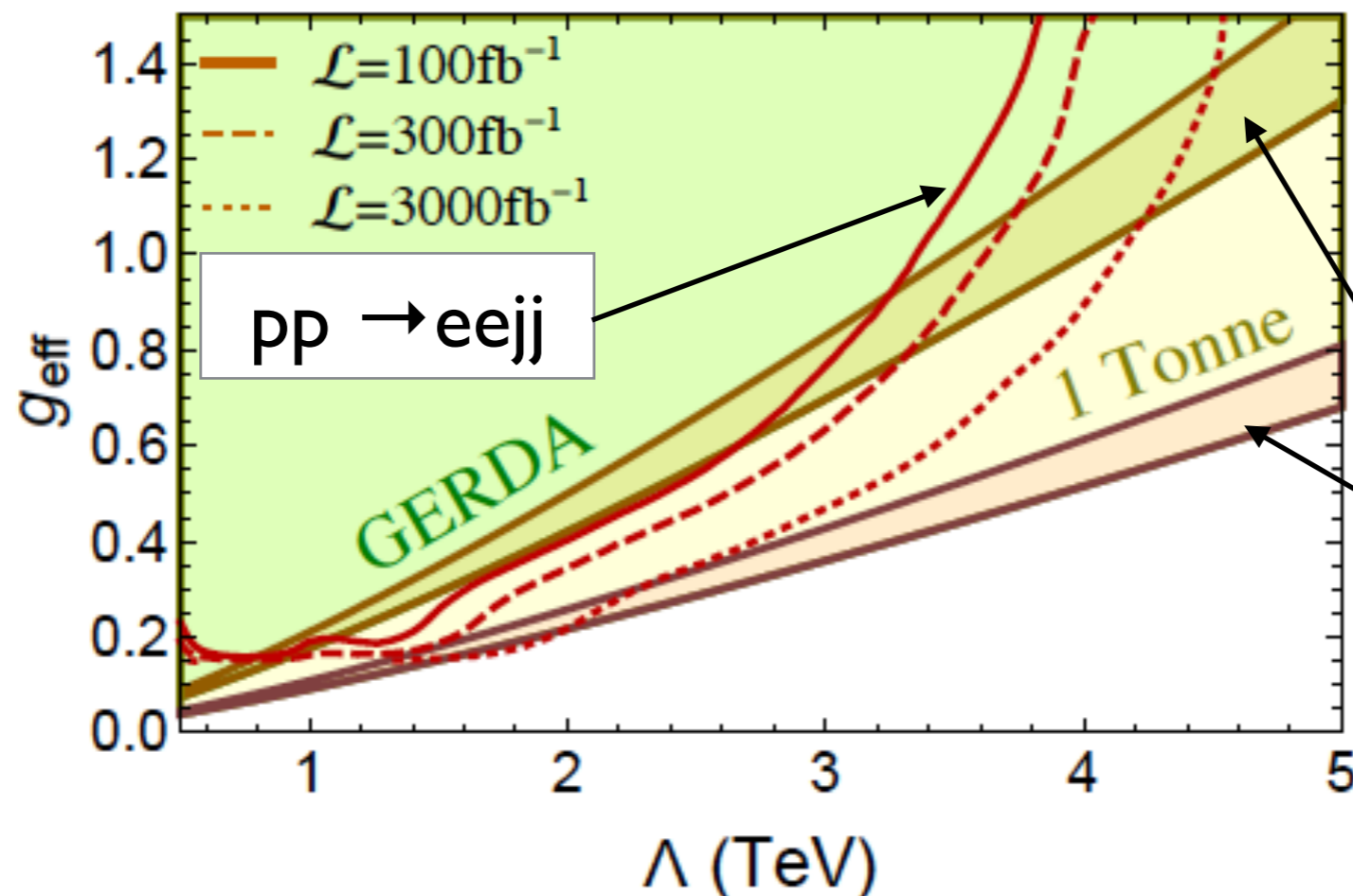
Second error:  
chiral corrections

# Impact on phenomenology

- Dim-9 ops ( $O_{2,3}$ ) from TeV-scale simplified model  $\sim$  RPV-SUSY



Peng, Ramsey-Musolf,  
Winslow, 1508.0444



Sensitivity study:  
 $0\nu\beta\beta$  vs LHC  
(current and future)

Plot assumes 30%  
uncertainty in the  
nuclear matrix  
elements  
and VSA for  $\pi\pi\pi$   
matrix element  
( $\sim 2 \times$  our result)

# Conclusions

- EFT approach provides a systematic framework to:
  - relate  $0\nu\beta\beta$  to underlying LNV dynamics (and to collider processes)
  - organize contributions to hadronic and nuclear matrix elements
- Chiral EFT analysis of light  $V_M$  exchange:
  - Identified potential to LO and N<sup>2</sup>LO
  - **Key new result:** leading order contact  $nn \rightarrow pp$  operator (LEC enhanced by  $(4\pi)^2$  compared to naive dimensional analysis)
  - $0\nu\beta\beta$  and electromagnetic LECs are related.  
Can be obtained via a (difficult) lattice QCD calculation

# Conclusions

- EFT approach provides a systematic framework to:
  - relate  $0\nu\beta\beta$  to underlying LNV dynamics (and to collider processes)
  - organize contributions to hadronic and nuclear matrix elements
- Chiral EFT analysis of short-distance LNV mechanisms:
  - Identified potential to LO
  - Estimated  $\pi\pi$  matrix elements from chiral symmetry + lattice Kaon matrix elements
  - More LQCD input: NN matrix elements of 4-quark operators